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# SIMULATION STUDY OF EFFECTS OF THRUST VECTORING AND INDUCED LIFT DUE TO THRUST VECTORING ON COMBAT EFFECTIVENESS OF A FIGHTER AIRCRAFT (U)

*Jack E. Pennington*

*Langley Research Center*
*Hampton, Va. 23665*

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# SIMULATION STUDY OF EFFECTS OF THRUST VECTORING AND INDUCED LIFT DUE TO THRUST VECTORING ON COMBAT EFFECTIVENESS OF A FIGHTER AIRCRAFT (U)

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## SUMMARY

As part of a research program to determine the usefulness of advanced concepts for improving the maneuverability of fighter-type aircraft, a simulation study has been conducted to examine the effects of thrust vectoring and induced lift on combat effectiveness. A simulated F-4 aircraft, assumed to have limited ($30^{\circ}$ maximum) thrust vectoring capability with or without an induced lift component, was flown against two opponent aircraft. One opponent was the same aircraft without vectoring, and the other was a hypothetical aircraft without vectoring but with superior turning performance.

Results showed that thrust vectoring, particularly with lift augmentation, can provide a significant improvement in maneuverability. Vectoring was used mostly at moderate and low subsonic speeds where it improved the turning capability of the F-4 aircraft. It was not used at high speeds probably because it caused the aircraft to decelerate and reduced the sustained turning capability.

## INTRODUCTION

In support of research related to advanced fighter technology, the Langley differential maneuvering simulator has been used to investigate the effects of advanced aerodynamic concepts and of changes in aircraft performance parameters on the one-on-one close-in capability of fighter aircraft. Changes which have been investigated include thrust-weight ratio $T/W$, wing loading $W/S$, maximum lift coefficient $C_{L,max}$, thrust reversing, and thrust vectoring.

One concept for improving the maneuverability of fighter aircraft is to employ a vectorable jet near or at the trailing edge of an airfoil. Studies (refs. 1 to 3) have shown that this can provide additional lift due to induced circulation over the airfoil. This report describes the simulation of limited thrust vectoring ($30^{\circ}$ maximum), with and without this induced lift, by using the F-4 aircraft as a baseline. The results obtained

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from engagements between the modified F-4 and the basic F-4 are discussed as well as engagements between the modified F-4 and a low-wing-loaded opponent.

## SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

| | |
|---|---|
| $C_D$ | drag coefficient |
| $C_{L,max}$ | maximum lift coefficient |
| $C_l$ | rolling-moment coefficient |
| $C_{l_\beta}$ | $= \frac{\partial C_l}{\partial \beta}$, per degree |
| $C_{l_{\delta r}}$ | $= \frac{\partial C_l}{\partial \delta_r}$, per degree |
| $C_n$ | yawing-moment coefficient |
| $C_{n_\beta}$ | $= \frac{\partial C_n}{\partial \beta}$, per degree |
| $C_{n_{\delta r}}$ | $= \frac{\partial C_n}{\partial \delta_r}$, per degree |
| $C_{X,t}, C_{L,t}$ | longitudinal and normal force coefficients due to thrust |
| $C_Y$ | side-force coefficient |
| $C_{Y_{\delta r}}$ | $= \frac{\partial C_Y}{\partial \delta_r}$, per degree |
| L/D | lift-drag ratio |
| M | Mach number |



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$P_S$ specific excess power, meters per second (feet per second)

$\bar{q}$ dynamic pressure, newtons per meter$^2$ (pounds per foot$^2$)

$r$ correlation coefficient

$S$ wing area, meters$^2$ (feet$^2$)

$T_{gross}$ gross thrust, newtons (pounds)

$T_{net}$ net thrust, newtons (pounds)

$T_{ram}$ decelerating force due to engine losses and ram drag, newtons (pounds)

$T_{x,b}, T_{y,b}, T_{z,b}$ components of thrust along X, Y, and Z body axis, respectively, newtons (pounds)

$T_{x,e}, T_{z,e}$ components of thrust along X and Z engine axis, respectively, newtons (pounds)

$T_{x,s}, T_{z,s}$ components of thrust along X and Z stability axis, respectively, newtons (pounds)

$t$ total time, 180 seconds

$V$ total aircraft velocity, meters per second (feet per second)

$W$ weight, kilograms (pounds)

$\alpha$ angle of attack, degrees

$\beta$ angle of sideslip, degrees

$\epsilon$ engine inclination angle, degrees

$\theta_j$ thrust vectoring angle, degrees

$\lambda$ line-of-sight angle, angle between X body axis and line-of-sight vector, degrees

Subscripts:

A attacking aircraft

e elevation

man maneuver conditions

max maximum

O opponent (HMA)

Abbreviations:

ACM air combat maneuvering

AML adaptive maneuvering logic

AMP aircraft maneuvering parameter

DMS differential maneuvering simulator

HMA highly maneuvering adversary (aircraft)

TOA time on offense with advantage

A dot over a symbol denotes derivative with respect to time.

## SIMULATED AIRCRAFT

The baseline aircraft used for this study was similar to the F-4E/J without slats. The basic characteristics of the simulated aircraft and the equations of motion used are presented in reference 4; however, for this study the lateral-directional stability data and the thrust computation were modified.

### Lateral-Directional Data Changes

Data for the stability derivatives $C_{l_\beta}$ and $C_{n_\beta}$ were changed to reflect newer, more realistic subsonic data (refs. 5 and 6) at high angles of attack ($\alpha > 15^o$). Figures 1 and 2 show the data from reference 4 and the data currently used. Data from references 5 and 6 showed a decrease in lateral-directional stability with increasing angle of attack but not as severe as that shown in reference 4.

### Rudder Effectiveness Change

Rudder effectiveness derivatives $C_{Y_{\delta r}}$ and $C_{n_{\delta r}}$ were not originally defined as functions of angle of attack because no data were available in early sources at high angles of attack, and little change was indicated at low angles of attack. However, later data (ref. 5) did show a marked decrease in control effectiveness at high angles of attack. Therefore, the rudder effectiveness derivatives were redefined as

$$C_{Y_{\delta r}} = K_r C^*_{Y_{\delta r}}$$

$$C_{n_{\delta r}} = K_r C^*_{n_{\delta r}}$$

where

$$K_r = 1 - 0.01\alpha \qquad (\alpha \leqq 25^\circ)$$

$$K_r = 0.75 - 0.045(\alpha - 25) \qquad (\alpha > 25^\circ)$$

and

$$0 \leqq K_r \leqq 1$$

The derivatives $C^*_{Y_{\delta r}}$ and $C^*_{n_{\delta r}}$, corresponding to the original definition of $C_{Y_{\delta r}}$ and $C_{n_{\delta r}}$, are shown in figures 3 and 4. No changes were made to $C_{l_{\delta r}}$ which was defined (ref. 4) as a function of angle of attack.

### Thrust Calculations

The net installed thrust (from ref. 4) was separated into a gross thrust component $T_{gross}$ and a component $T_{ram}$ representing ram drag and engine losses. The gross thrust was assumed to be vectorable through an angle $\theta_j$ from the engine axis. The deceleration component $T_{ram}$ was assumed to remain alined with the engine axis. Gross thrust and ram drag were computed as follows:

$$T_{gross} = T_{net}(1 + 0.377M)$$

$$T_{ram} = T_{net}(0.377M)$$

Components of thrust along and normal to the engine axis were computed as

$$T_{x,e} = T_{gross} \cos \theta_j - T_{ram}$$

$$T_{z,e} = -K_j T_{gross} \sin \theta_j$$

where $K_j$ is a multiplier used to simulate induced lift effects. For the basic aircraft, $\theta_j$ equals 0.

For thrust vectoring without induced lift, $\theta_j$ was controlled by the pilot and $K_j = 1$. For thrust vectoring with induced lift $\theta_j$ was controlled by the pilot and $K_j = 2$. Thus, the induced lift was simulated as equal to the component of gross thrust perpendicular to the engine axis.

Components of thrust and induced lift force in the aircraft body axis system were computed as

$$T_{x,b} = T_{x,e} \cos \epsilon + T_{z,e} \sin \epsilon$$

$$T_{y,b} = 0$$

$$T_{z,b} = -T_{x,e} \sin \epsilon + T_{z,e} \cos \epsilon$$

$$\epsilon = 5.25^{\circ}$$

where $\epsilon$ is the engine inclination angle with respect to the X body axis (positive upward).

Transforming the components of thrust from body to stability axis gives

$$T_{x,s} = T_{x,b} \cos \alpha + T_{z,b} \sin \alpha$$

$$T_{z,s} = -T_{x,b} \sin \alpha + T_{z,b} \cos \alpha$$

Substituting for $T_{x,b}$ and $T_{z,b}$ gives components of thrust along the X and Z stability axes due to thrust vectoring $\left((T_{x,s})_v \text{ and } (T_{z,s})_v\right)$, ram drag $\left((T_{x,s})_d \text{ and } (T_{z,s})_d\right)$, and induced lift $\left((T_{x,s})_l \text{ and } (T_{z,s})_l\right)$.

$$T_{x,s} = \underbrace{T_{gross} \cos \left(\theta_j + \alpha + \epsilon\right)}_{(T_{x,s})_v} - \underbrace{T_{ram} \cos (\alpha + \epsilon)}_{(T_{x,s})_d} - \underbrace{\left(K_j - 1\right) T_{gross} \sin \theta_j \sin (\alpha + \epsilon)}_{(T_{x,s})_l}$$

$$T_{z,s} = \underbrace{-T_{gross} \sin \left(\theta_j + \alpha + \epsilon\right)}_{(T_{z,s})_v} + \underbrace{T_{ram} \sin (\alpha + \epsilon)}_{(T_{z,s})_d} - \underbrace{\left(K_j - 1\right) T_{gross} \sin \theta_j \cos (\alpha + \epsilon)}_{(T_{z,s})_l}$$

Since aircraft drag $C_D$ acts along the -X stability axis (parallel to the velocity vector) and aircraft lift acts along the -Z stability axis (normal to the velocity vector), the equations show that

(1) At fixed $\alpha$, as $\theta_j$ increases, the aircraft "sees" an apparent increase in lift because $(T_{z,s})_v$ and $(T_{z,s})_l$ $\left(\text{if } K_j = 2\right)$ increase with $\theta_j$ and $(T_{z,s})_d$ remains fixed.

(2) With this increase in lift there is an associated apparent loss of thrust (reduced $T_{x,s}$) because $(T_{x,s})_v$ decreases with $\theta_j$, $(T_{x,s})_l$ increases $\left(\text{if } K_j = 2\right)$, and $(T_{x,s})_d$ remains fixed.

(3) The effect of angle of attack on $T_{x,s}$ and $T_{z,s}$ depends on the magnitude of $T_{gross}$, $T_{ram}$, and $\theta_j$. However, increasing $\alpha$ tends to increase $(T_{x,s})_l$ which tends to reduce $T_{x,s}$, and it tends to decrease $(T_{z,s})_l$, which appears as a loss in lift. This effect is illustrated in figure 5 which shows the thrust and lift coefficients $C_{X,t}$ and $C_{L,t}$ as a function of angle of attack, for simulated aircraft, where

$$C_{X,t} = \frac{T_{x,s}}{\bar{q}S}$$

$$C_{L,t} = \frac{-T_{z,s}}{\bar{q}S}$$

## Performance

Figure 6 shows the specific excess power $P_S$ for the baseline aircraft, the vectored aircraft, and the aircraft with vectoring and lift augmentation at $M = 0.6$ and an altitude of 3048 meters (10 000 feet), where

$$P_S = \left(T_{x,s} - C_D\bar{q}S\right)\frac{V}{W}$$

The aircraft with 30° vectoring $\left(\theta_j = 30^\circ\right)$ showed about 0.1g lower sustained normal acceleration, about 0.4g higher maximum normal acceleration, and considerably lower excess thrust at cruise (1g) conditions. The aircraft with vectoring plus lift augmentation had the same sustained normal acceleration as the baseline aircraft, about 0.8g higher maximum acceleration, and the lowest $P_S$ at 1g. Compared with the vectored aircraft, the lift augmentation provided better sustained and instantaneous normal acceleration with only a small penalty in level flight acceleration.

Figure 7 shows the sustained turn-rate capability at altitudes of 3048 and 9144 meters (10 000 and 30 000 feet) for the three aircraft. The vectoring plus lift augmentation improved the aircraft turn-rate capability at low speeds and reduced it at high subsonic and supersonic speeds. The best sustained turn rate then would be obtained by using vectoring below about $M = 0.6$ and no vectoring above $M = 0.6$. Vectoring did not improve the sustained turn rate at high speeds because of the reduced longitudinal acceleration. However, the associated rapid deceleration capability might be useful in some situations.

### Assumptions Associated With Simulating Thrust Vectoring

In addition to assumptions involved in simulating the basic F-4, which are discussed in reference 4, the following assumptions were made for this study:

(1) No disturbing moments were generated by vectoring the thrust

(2) The magnitude of gross thrust and ram drag is unaffected by angle of attack and thrust vector angle

(3) The vector angle followed the pilot's command without delay or lag

(4) The thrust could be vectored at all throttle settings including afterburning

(5) No weight penalty was assessed for the addition of vectoring to the F-4

## HIGHLY MANEUVERING ADVERSARY (HMA) AIRCRAFT

Since vectoring capability was simulated without including a weight or thrust penalty, the modified F-4 aircraft would have maneuvering capability at least as good as the basic F-4. Thus, simulated engagements between the basic F-4 and the modified F-4 would indicate the amount of improvement (if any) provided by thrust vectoring.

It was also desirable to simulate an aircraft significantly superior to the basic F-4 and to determine whether vectoring the F-4 thrust could reduce or eliminate the superiority.

Such an aircraft, called the highly maneuvering adversary (HMA) aircraft, was simulated and flown against both the basic F-4 and the F-4 with thrust vectoring plus induced lift. The HMA aircraft is described in reference 7. It was assumed to be a lightweight fixed-wing fighter having higher control effectiveness than the F-4, lower wing loading ($W/S \approx 3100$ N/m$^2$ (65 lb/ft$^2$) for HMA and $W/S \approx 3700$ N/m$^2$ (77 lb/ft$^2$) for F-4), about the same thrust-weight ratio ($T/W \approx 0.8$), and slightly higher maximum lift coefficient. These characteristics gave the HMA maneuvering capabilities superior to the basic F-4 at all subsonic speeds and made it a formidable opponent for the modified F-4.

## SIMULATION PROCEDURE

Five cases (aircraft combinations) were studied, as shown in table 1.

TABLE 1.- CASES STUDIED

| Case | Modified F-4 | | Opponent |
|---|---|---|---|
| | Vectoring | Lift augmentation | |
| 1 | No | No | Basic F-4 |
| 2 | No | No | HMA |
| 3 | Yes | No | Basic F-4 |
| 4 | Yes | Yes | Basic F-4 |
| 5 | Yes | Yes | HMA |

The "modified" aircraft without vectoring or lift augmentation (case 1) was identical to the basic F-4. Vectoring was simulated by modifying the logic for the two throttle levers in the DMS cockpit so that the outside throttle lever commanded thrust for both engines and the inside lever commanded thrust vector angle. The vector angle varied linearly from $\theta_j = 0^\circ$ for inboard throttle full forward to $\theta_j = 30^\circ$ for throttle full aft (idle thrust setting). A cockpit instrument displayed thrust vector angle to the pilot.

Each case was flown by a group of four combat-qualified pilots, with each pilot in a group flying two simulated engagements against each other pilot in the same group in each aircraft. Engagements were started with the aircraft at an altitude of 4572 meters (15 000 feet), $M = 0.9$, and head-on at 3660-meter (12 000-foot) range. Data runs lasted 3 minutes; any run which ended earlier because of impacting the ground or departure (spin) was recorded but not used for data. Sixty-two variables, describing the state of each aircraft and the pilot inputs, were recorded on magnetic tape every 0.5 second during a run for later processing. Two groups of combat-qualified pilots participated in the study. One group flew all five cases (table 1); the other group flew all except case 3.

## ANALYSIS AND SCORING

Several different criteria were used to evaluate the outcome of simulated engagements. These criteria described in reference 8 include (1) time on offense with advantage, (2) probability of conversion, (3) time to convert, (4) time in gun zone, and (5) adaptive maneuvering logic (AML) value, and each is discussed in the following sections.

### Time on Offense With Advantage

Time on offense with advantage (TOA) for an aircraft is defined as the time that the aircraft is in the opponent's rear hemisphere (opponent's line-of-sight angle $\lambda_O$ exceeds

$90^{\circ}$) and has the opponent in his front hemisphere ($\lambda_A < 90^{\circ}$). The line-of-sight angle $\lambda$ is defined as the angle between the $X$ body axis and the line-of-sight vector to the other aircraft. Time on offense with advantage provides a quantitative measure of aircraft capability and in previous studies (refs. 4 and 9) has correlated well with pilot opinion and other quantitative measures.

## Time To Convert and Time in Gun Zone

An aircraft was assumed to have achieved a gun conversion (firing opportunity) when (1) range was less than 914 meters (3000 feet), (2) aircraft line-of-sight angle $\lambda_A$ was less than $10^{\circ}$, and (3) opponent's line-of-sight angle $\lambda_O$ exceeded $120^{\circ}$. Probability of conversion was defined as the percent of engagements in which conversion occurred. Time in gun zone was the total time that the aircraft satisfied these criteria.

## AML Value

The AML value is based on quantitative criteria used by the Langley Adaptive Maneuvering Logic (AML) computer program. This program (ref. 10) is a digital model of a one-on-one air combat engagement. The program can be run in an off-line (batch) mode, or the decision and maneuvering logic can be used to supply a computer-driven opponent for a pilot in the DMS. The decision logic in the program tries to adaptively improve the AML value, which is calculated based on the questions in table 2. If the answer to a question is yes for an aircraft (assumed to be the attacker), a 1 is assigned; if not, a 0 is assigned. The AML value is just the sum of the 11 assigned values and is calculated separately for each aircraft.

For each simulated engagement the AML value was computed for each aircraft every 0.5 second and then averaged over the 3 minutes of the engagement. Previous studies have shown that a difference of 1.0 in AML values indicates a definite aircraft superiority. The elevation component of the line-of-sight angle $\lambda_{A,e}$ is measured from the $X$-$Y$ plane of the body axes to the center of gravity of the opponent, positive up. The deviation angle $\xi$ is defined as the angle between the velocity vector of the attacker and the line-of-sight vector; $R$ is the range.

# RESULTS

For each case studied the average time on offense with advantage, time in gun zone, and AML value were computed by averaging over the total number of runs flown (24). The probability of conversion was computed as the fraction of runs in which a conversion occurred. Average time to convert was computed by averaging over the number of runs in which the aircraft achieved a conversion.

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TABLE 2.- QUESTIONS USED TO ASSIGN AML VALUE

| Question | Criteria (a) |
| --- | --- |
| 1. Is opponent ahead of attacker? | $\lambda_A < 90^o$ |
| 2. Is attacker behind opponent? | $\lambda_O > 90^o$ |
| 3. Can attacker see opponent? | $-30^o < \lambda_{A,e} < 150^o$ |
| 4. Is opponent unable to see attacker? | $\lambda_{O,e} > 150^o$ or $\lambda_{O,e} < -30^o$ |
| 5. Is attacker in volume behind opponent? | ($\lambda_O > 150^o$ and $R < 914$ m) or<br>($\lambda_O > 135^o$ and $914 < R < 1524$ m) |
| 6. Is opponent outside of volume behind attacker? | $R > 1524$ m or $\lambda_A < 150^o$ if<br>$R < 914$ m or $\lambda_A < 135^o$ if<br>$914 < R < 1524$ m |
| 7. Can attacker fire at opponent? | $\lambda_A < 30^o$ and $R < 914$ m |
| 8. Is opponent unable to fire at attacker? | $\lambda_O > 30^o$ or $R > 914$ m |
| 9. Are aircraft closing slowly? | $-91$ m/sec $< \dot{R} < 0$ |
| 10. Is attacker deviation angle below 60°? | $\xi < 60^o$ |
| 11. Is attacker line of sight decreasing? | $\dot{\lambda}_A < 0^o$/sec |

[a] 914 m = 3000 ft; 1524 m = 5000 ft; and -91 m/sec = -300 ft/sec.

## Equal Aircraft

The first study conducted with each group of pilots was a set of simulated combat engagements between equal aircraft (F-4's). Table 3 summarizes the results for the two groups.

TABLE 3.- RESULTS FOR EQUAL AIRCRAFT

| Scoring criteria | Group 1 | Group 2 |
| --- | --- | --- |
| Average TOA at 180 sec . . . . . . . . | 36.0 | 46.6 |
| Probability of conversion . . . . . . . | 4/24 | 5/24 |
| Average time to convert, sec . . . . . | 138.3 | 152.0 |
| Average time in gun zone, sec . . . . . | 3.0 | 0.9 |
| Average AML value . . . . . . . . . . | 5.2 | 5.2 |

Figure 8 shows the average TOA at various times into the run for each pilot group involved in the study, with each DMS cockpit treated as a separate aircraft. Since the

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aircraft definition and simulator cockpits were identical for each aircraft, the difference in TOA is considered to be due to the pilots and the way they flew the aircraft.

The data in table 3 show, as expected, that with equal aircraft it was difficult to achieve a gun conversion. The few conversions that occurred were achieved late in the run.

## Unmodified F-4 Flown Against HMA

The second case studied was the basic (unmodified) F-4 flown against the simulated HMA. Each group of pilots made 24 data runs for this case.

Figure 9 shows the average time on offense with advantage (TOA) as a function of time into the run. Figure 10 compares the average TOA at 180 sec (end of run) for this case with the TOA obtained with equal aircraft. The HMA maneuvering superiority enabled the HMA to convert early in the run and maintain an advantageous position. The superiority is corroborated by the other results shown in table 4.

TABLE 4.- RESULTS FOR BASIC F-4 FLOWN AGAINST HMA

| Scoring criteria | Group 1 | | Group 2 | |
|---|---|---|---|---|
| | F-4 | HMA | F-4 | HMA |
| Average TOA at 180 sec . . . . . . . | 3.8 | 106.7 | 15.9 | 88.4 |
| Probablility of conversion . . . . . . | 0 | 19/24 | 0 | 15/24 |
| Average time to convert, sec . . . . | --- | 116.7 | --- | 93.4 |
| Average time in gun zone, sec . . . . | 0 | 22.6 | 0 | 14.5 |
| Average AML value . . . . . . . . . | 3.7 | 6.9 | 4.0 | 6.6 |

All data in table 4 indicate that the HMA was superior to the basic F-4. The second group of pilots appeared to do better in the F-4 (or poorer in the HMA) as indicated by the smaller disparity in TOA and AML values.

## Basic F-4 Flown Against F-4 With 30° Thrust Vectoring

One group of pilots flew the basic F-4 against the simulated F-4 having the same characteristics but with the inclusion of vectored thrust (case 3 in table 1). Table 5 shows the results for this case. The results indicate that the aircraft with vectoring capability had some advantage. The probability of conversion was about the same for both aircraft, but average TOA, average time in gun zone, and average AML indicate that vectoring provided a significant improvement.

TABLE 5.- RESULTS FOR BASIC F-4 FLOWN AGAINST F-4 WITH THRUST VECTORING

| Scoring criteria | Basic F-4 | F-4 with vectoring |
|---|---|---|
| Average TOA at 180 sec . . . . . . . . . | 35.4 | 71.7 |
| Probability of conversion . . . . . . . . | 5/24 | 7/24 |
| Average time to convert, sec . . . . . . | 123.2 | 86.4 |
| Average time in gun zone, sec . . . . . . | 2.0 | 10.1 |
| Average AML value . . . . . . . . . . . | 4.8 | 5.8 |

The data for the aircraft with vectoring were examined to determine the conditions under which vectoring was used. Percent of total run time and time on offense with advantage were computed for several intervals of Mach number, angle of attack, and vector angle. These data are presented in tables 6 and 7 and plotted in figures 11 and 12.

TABLE 6.- PERCENT OF TOTAL TIME (180 SECONDS) WITHIN THRUST VECTORING INTERVALS

| Angle of attack | Mach number | Percent of total time within – | | |
|---|---|---|---|---|
| | | $0^{\circ} \leqq \theta_j < 10^{\circ}$ | $10^{\circ} \leqq \theta_j \leqq 20^{\circ}$ | $20^{\circ} < \theta_j \leqq 30^{\circ}$ |
| $\alpha < 10^{\circ}$ | M < 0.4 | 4.33 | 0.52 | 4.05 |
| | 0.4 to 0.6 | 6.45 | 0.70 | 4.44 |
| | 0.6 to 0.8 | 4.44 | 0.17 | 0.94 |
| | 0.8 to 1.0 | 4.12 | 0 | 0.33 |
| | M > 1.0 | 0.06 | 0 | 0 |
| $10^{\circ} \leqq \alpha \leqq 20^{\circ}$ | M < 0.4 | 4.63 | 0.61 | 5.28 |
| | 0.4 to 0.6 | 8.45 | 1.49 | 6.42 |
| | 0.6 to 0.8 | 6.45 | 0.37 | 0.83 |
| | 0.8 to 1.0 | 2.58 | 0 | 0.36 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^{\circ}$ | M < 0.4 | 3.15 | 0.35 | 4.04 |
| | 0.4 to 0.6 | 7.20 | 1.55 | 7.36 |
| | 0.6 to 0.8 | 5.70 | 0.63 | 1.35 |
| | 0.8 to 1.0 | 0.63 | 0 | 0.01 |
| | M > 1.0 | 0 | 0 | 0 |

[redacted]

TABLE 7.- PERCENT OF AVERAGE TOA (71.7 SECONDS) WITHIN THRUST VECTORING INTERVALS

| Angle of attack | Mach number | Percent of TOA within – | | |
|---|---|---|---|---|
| | | $0^\circ \leq \theta_j < 10^\circ$ | $10^\circ \leq \theta_j \leq 20^\circ$ | $20^\circ < \theta_j \leq 30^\circ$ |
| $\alpha < 10^\circ$ | M < 0.4 | 4.47 | 0.40 | 4.10 |
| | 0.4 to 0.6 | 9.44 | 0.61 | 5.57 |
| | 0.6 to 0.8 | 6.47 | 0.12 | 1.30 |
| | 0.8 to 1.0 | 1.47 | 0 | 0.09 |
| | M > 1.0 | 0.06 | 0 | 0 |
| $10^\circ \leq \alpha \leq 20^\circ$ | M < 0.4 | 3.72 | 0.43 | 4.71 |
| | 0.4 to 0.6 | 11.29 | 1.50 | 6.76 |
| | 0.6 to 0.8 | 7.25 | 0.49 | 1.30 |
| | 0.8 to 1.0 | 0.72 | 0 | 0.38 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 0.87 | 0.46 | 2.80 |
| | 0.4 to 0.6 | 7.62 | 1.07 | 7.33 |
| | 0.6 to 0.8 | 4.33 | 1.21 | 1.27 |
| | 0.8 to 1.0 | 0.40 | 0 | 0 |
| | M > 1.0 | 0 | 0 | 0 |

The data from tables 6 and 7 are plotted in figure 11 for all angles of attack. The figure shows several interesting results:

(1) Almost half the time (both run time and TOA) was spent at speeds between $M = 0.4$ and $M = 0.6$; the remainder was about equally divided below $M = 0.4$ and above $M = 0.6$. This is typical of most DMS engagements which degenerated to subsonic maneuvering.

(2) The use of thrust vectoring generally occurred below $M = 0.6$. This is consistent with figure 7 which indicated that this is the region in which thrust vectoring was most beneficial.

(3) Very little time was spent at vectoring angles between $10^\circ$ and $20^\circ$. This indicates that the pilots either did not find a use for intermediate deflections or did not need them.



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Figure 12 shows the data in angle-of-attack intervals at all Mach numbers. The figure indicates that thrust vector angle, TOA, and run time do not appear to be functions of angle of attack.

## Basic F-4 Flown Against F-4 With Thrust Vectoring and Lift Augmentation

Both groups of pilots flew the basic F-4 against the simulated F-4 having the vectored thrust plus lift augmentation (case 4 in table 1). Table 8 shows the results for this case.

TABLE 8.- RESULTS FOR BASIC F-4 FLOWN AGAINST F-4 WITH THRUST VECTORING AND LIFT AUGMENTATION

| Scoring criteria | Group 1 | | Group 2 | |
|---|---|---|---|---|
| | Basic | Vectoring | Basic | Vectoring |
| Average TOA at 180 sec . . . . . . . . . . | 5.4 | 69.9 | 26.0 | 83.7 |
| Probability of conversion . . . . . . . . . | 0 | 7/24 | 3/24 | 15/24 |
| Average time to convert, sec . . . . . . | --- | 131.5 | 139.2 | 96.9 |
| Average time in gun envelope, sec . . . | 0 | 5.7 | 0.5 | 12.2 |
| Average AML value . . . . . . . . . . . . | 4.5 | 6.0 | 4.4 | 6.1 |

Figure 13 summarizes the TOA at 180 sec for the data from cases 1 to 4. Pilot group 2 flying the F-4 with thrust vectoring and lift augmentation (case 4) showed improved TOA over case 3 (without lift augmentation) but lower TOA than that in case 2 against the hypothetical opponent.

Tables 9 to 12 present the percent of total run time and TOA in Mach number, angle of attack, and vector angle intervals averaged over the 24 runs. The data are plotted against Mach number (for all angles of attack) in figures 14 and 15. Figure 14 shows that both pilot groups spent about 80 percent of the run time at speeds below $M = 0.6$. Similarly, figure 15 shows that both groups obtained about 85 percent of their TOA at speeds below $M = 0.6$. However, both figures show that the second group used thrust vectoring more at these speeds.

[redacted]

TABLE 9.- PERCENT OF TOTAL TIME (180 SECONDS) WITHIN THRUST VECTORING INTERVALS FOR GROUP 1 FLYING F-4 WITH THRUST VECTORING PLUS INDUCED LIFT

| Angle of attack | Mach number | Percent of total time within – | | |
|---|---|---|---|---|
| | | $0^\circ \leq \theta_j < 10^\circ$ | $10^\circ \leq \theta_j \leq 20^\circ$ | $20^\circ < \theta_j \leq 30^\circ$ |
| $\alpha < 10^\circ$ | M < 0.4 | 2.44 | 0.82 | 5.00 |
| | 0.4 to 0.6 | 3.79 | 0.45 | 1.97 |
| | 0.6 to 0.8 | 1.50 | 0.05 | 0.38 |
| | 0.8 to 1.0 | 4.33 | 0.21 | 0.53 |
| | M > 1.0 | 0.01 | 0 | 0 |
| $10^\circ \leq \alpha \leq 20^\circ$ | M < 0.4 | 3.08 | 1.39 | 7.11 |
| | 0.4 to 0.6 | 8.05 | 1.37 | 4.18 |
| | 0.6 to 0.8 | 3.90 | 0.31 | 0.98 |
| | 0.8 to 1.0 | 1.78 | 0.18 | 1.50 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 3.90 | 1.77 | 12.41 |
| | 0.4 to 0.6 | 10.68 | 2.30 | 7.75 |
| | 0.6 to 0.8 | 3.38 | 0.60 | 1.02 |
| | 0.8 to 1.0 | 0.46 | 0.13 | 0.30 |
| | M > 1.0 | 0 | 0 | 0 |

TABLE 10.- PERCENT OF TOTAL TIME WITHIN THRUST VECTORING INTERVALS FOR PILOT GROUP 2 FLYING F-4 WITH THRUST VECTORING PLUS INDUCED LIFT

| Angle of attack | Mach number | Percent of total time within – | | |
|---|---|---|---|---|
| | | $0^\circ \leq \theta_j < 10^\circ$ | $10^\circ \leq \theta_j \leq 20^\circ$ | $20^\circ < \theta_j \leq 30^\circ$ |
| $\alpha < 10^\circ$ | M ≤ 0.4 | 1.77 | 0.55 | 9.07 |
| | 0.4 to 0.6 | 4.42 | 0.96 | 6.33 |
| | 0.6 to 0.8 | 2.74 | 0.20 | 1.05 |
| | 0.8 to 1.0 | 3.90 | 0.06 | 0.07 |
| | M > 1.0 | 0 | 0 | 0 |
| $10^\circ \leq \alpha \leq 20^\circ$ | M < 0.4 | 2.68 | 0.58 | 7.92 |
| | 0.4 to 0.6 | 6.17 | 2.06 | 9.43 |
| | 0.6 to 0.8 | 4.85 | 0.59 | 1.07 |
| | 0.8 to 1.0 | 3.33 | 0.30 | 0.08 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 1.98 | 0.45 | 6.36 |
| | 0.4 to 0.6 | 4.38 | 1.59 | 9.95 |
| | 0.6 to 0.8 | 2.91 | 0.77 | 1.06 |
| | 0.8 to 1.0 | 0.37 | 0.07 | 0 |
| | M > 1.0 | 0 | 0 | 0 |



[redacted]

TABLE 11.- PERCENT OF TOA (70.4 SECONDS) WITHIN THRUST VECTORING INTERVALS FOR PILOT GROUP 1 FLYING F-4 WITH THRUST VECTORING PLUS INDUCED LIFT

| Angle of attack | Mach number | Percent of TOA within – | | |
|---|---|---|---|---|
| | | $0^\circ \leqq \theta_j < 10^\circ$ | $10^\circ \leqq \theta_j \leqq 20^\circ$ | $20^\circ < \theta_j \leqq 30^\circ$ |
| $\alpha < 10^\circ$ | M < 0.4 | 2.61 | 0.24 | 3.94 |
| | 0.4 to 0.6 | 5.54 | 0.27 | 1.75 |
| | 0.6 to 0.8 | 1.63 | 0 | 0.53 |
| | 0.8 to 1.0 | 0.62 | 0 | 0.03 |
| | M > 1.0 | 0 | 0 | 0 |
| $10^\circ \leqq \alpha \leqq 20^\circ$ | M < 0.4 | 3.82 | 1.04 | 6.25 |
| | 0.4 to 0.6 | 10.45 | 1.48 | 4.50 |
| | 0.6 to 0.8 | 4.50 | 0.12 | 0.71 |
| | 0.8 to 1.0 | 0.38 | 0 | 0.38 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 5.48 | 3.20 | 10.95 |
| | 0.4 to 0.6 | 13.08 | 3.32 | 7.79 |
| | 0.6 to 0.8 | 3.82 | 0.36 | 0.92 |
| | 0.8 to 1.0 | 0.21 | 0.09 | 0.03 |
| | M > 1.0 | 0 | 0 | 0 |

TABLE 12.- PERCENT OF TOA (83.7 SECONDS) WITHIN THRUST VECTORING INTERVALS FOR PILOT GROUP 2 FLYING F-4 WITH THRUST VECTORING PLUS INDUCED LIFT

| Angle of attack | Mach number | Percent of TOA within – | | |
|---|---|---|---|---|
| | | $0^\circ \leqq \theta_j < 10^\circ$ | $10^\circ \leqq \theta_j \leqq 20^\circ$ | $20^\circ < \theta_j \leqq 30^\circ$ |
| $\alpha < 10^\circ$ | M < 0.4 | 2.28 | 0.40 | 12.60 |
| | 0.4 to 0.6 | 4.23 | 1.21 | 7.92 |
| | 0.6 to 0.8 | 2.43 | 0.25 | 1.51 |
| | 0.8 to 1.0 | 1.29 | 0 | 0.15 |
| | M > 1.0 | 0 | 0 | 0 |
| $10^\circ \leqq \alpha \leqq 20^\circ$ | M < 0.4 | 3.79 | 0.79 | 7.97 |
| | 0.4 to 0.6 | 6.71 | 2.33 | 10.47 |
| | 0.6 to 0.8 | 2.67 | 0.52 | 1.49 |
| | 0.8 to 1.0 | 0.89 | 0.02 | 0.17 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 2.55 | 0.72 | 4.93 |
| | 0.4 to 0.6 | 4.61 | 2.01 | 10.50 |
| | 0.6 to 0.8 | 1.04 | 0.35 | 0.97 |
| | 0.8 to 1.0 | 0.25 | 0 | 0 |
| | M > 1.0 | 0 | 0 | 0 |

## F-4 With Thrust Vectoring Plus Lift Augmentation Flown Against HMA

The final case, flown by both pilot groups, was the F-4 with thrust vectoring and lift augmentation flown against the HMA. Based on previous results (fig. 13) it was anticipated that the HMA would be slightly superior. Table 13 shows the results for this case.

TABLE 13.- RESULTS FOR MODIFIED F-4 FLOWN AGAINST HMA

| Scoring criteria | Group 1 | | Group 2 | |
|---|---|---|---|---|
| | F-4 | HMA | F-4 | HMA |
| Average TOA at 180 sec . . . . . . . . | 38.8 | 25.9 | 44.3 | 66.5 |
| Probability of conversion . . . . . . | 4/24 | 1/24 | 4/24 | 11/24 |
| Average time to convert, sec . . . . | 117.4 | 134.0 | 91.4 | 115.3 |
| Average time in gun zone, sec . . . . | 0.2 | 0.1 | 3.2 | 7.2 |
| Average AML value . . . . . . . . . | 5.4 | 5.1 | 4.9 | 5.6 |

The overall results do not indicate a clear superiority for either aircraft. Pilot group 1 did better in the modified F-4, and pilot group 2 did better in the HMA. Both groups had a large number of runs without a gun conversion. Pilot group 1 had a relatively small difference in AML values. Thus, it appears that the maneuvering superiority or inferiority of the two simulated aircraft cannot be established from this statistical base. This is a problem in such manned simulations. Despite the use of qualified pilots, large variations are sometimes seen in the results, particularly for more evenly matched aircraft. Thus, the more nearly equal the aircraft are, the larger the statistical base required to have confidence in the results.

Tables 14 to 17 present the data from case 5 relating to thrust vector usage. The percents of run time and TOA in intervals of Mach number and thrust vector angle are plotted in figures 16 and 17. The figures may suggest one explanation for the difference in outcome for the two pilot groups. Comparison of figures 16 and 17 shows strong correlation between average percent of run time (fig. 16) and TOA (fig. 17) for both pilot groups; this indicates that TOA was related to run time in the various intervals. The difference in percent of run time in the different Mach number regimes (figs. 16(a) and 16(b)) is sizable. Pilot group 1 spent about 20 percent more time at low speed ($M < 0.4$) than group 2 and about 10 percent less time at $0.4 < M \leqq 0.6$. As was shown earlier (fig. 7), the thrust vectoring with lift augmentation provides the biggest payoff in the low-speed regime. Therefore. the first pilot group may have been able to make more use of the capability of the modified aircraft.

[redacted]

TABLE 14.- PERCENT OF TOTAL TIME (180 SECONDS) WITHIN THRUST VECTORING INTERVALS FOR PILOT GROUP 1

| Angle of attack | Mach number | Percent of total time within – | | |
|---|---|---|---|---|
| | | $0^\circ \leqq \theta_j < 10^\circ$ | $10^\circ \leqq \theta_j \leqq 20^\circ$ | $20^\circ < \theta_j \leqq 30^\circ$ |
| $\alpha < 10^\circ$ | M < 0.4 | 2.67 | 0.25 | 7.30 |
| | 0.4 to 0.6 | 0.84 | 0.24 | 2.10 |
| | 0.6 to 0.8 | 0.28 | 0.01 | 0.18 |
| | 0.8 to 1.0 | 3.51 | 0.31 | 0.46 |
| | M > 1.0 | 0 | 0 | 0.02 |
| $10^\circ \leqq \alpha \leqq 20^\circ$ | M < 0.4 | 1.72 | 0.26 | 13.47 |
| | 0.4 to 0.6 | 2.49 | 0.20 | 4.78 |
| | 0.6 to 0.8 | 1.82 | 0.51 | 1.29 |
| | 0.8 to 1.0 | 0.85 | 0.40 | 1.35 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 1.11 | 0.28 | 29.83 |
| | 0.4 to 0.6 | 3.30 | 0.81 | 13.42 |
| | 0.6 to 0.8 | 0.94 | 0.28 | 1.65 |
| | 0.8 to 1.0 | 0.63 | 0.10 | 0.33 |
| | M > 1.0 | 0 | 0 | 0 |

TABLE 15.- PERCENT OF TOTAL TIME (180 SECONDS) WITHIN THRUST VECTORING INTERVALS FOR PILOT GROUP 2

| Angle of attack | Mach number | Percent of total time within – | | |
|---|---|---|---|---|
| | | $0^\circ \leqq \theta_j < 10^\circ$ | $10^\circ \leqq \theta_j \leqq 20^\circ$ | $20^\circ < \theta_j \leqq 30^\circ$ |
| $\alpha < 10^\circ$ | M < 0.4 | 4.08 | 0.15 | 6.98 |
| | 0.4 to 0.6 | 5.09 | 0.26 | 3.21 |
| | 0.6 to 0.8 | 3.86 | 0 | 0.32 |
| | 0.8 to 1.0 | 5.09 | 0.01 | 0.40 |
| | M > 1.0 | 1.02 | 0 | 0 |
| $10^\circ \leqq \alpha \leqq 20^\circ$ | M < 0.4 | 2.82 | 0.29 | 9.91 |
| | 0.4 to 0.6 | 4.69 | 0.61 | 7.84 |
| | 0.6 to 0.8 | 3.27 | 0.03 | 1.25 |
| | 0.8 to 1.0 | 2.76 | 0 | 0.07 |
| | M > 1.0 | 0.20 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 1.40 | 0.12 | 11.06 |
| | 0.4 to 0.6 | 5.20 | 1.17 | 10.82 |
| | 0.6 to 0.8 | 3.53 | 0.08 | 1.78 |
| | 0.8 to 1.0 | 0.55 | 0.01 | 0.05 |
| | M > 1.0 | 0 | 0 | 0 |

[redacted]

TABLE 16.- PERCENT OF TOA (38.8 SECONDS) WITHIN THRUST VECTORING INTERVALS FOR PILOT GROUP 1

| Angle of attack | Mach number | Percent of TOA within – | | |
|---|---|---|---|---|
| | | $0^\circ \leqq \theta_j < 10^\circ$ | $10^\circ \leqq \theta_j \leqq 20^\circ$ | $20^\circ < \theta_j \leqq 30^\circ$ |
| $\alpha < 10^\circ$ | M < 0.4 | 3.22 | 0.11 | 5.15 |
| | 0.4 to 0.6 | 0.43 | 1.07 | 2.52 |
| | 0.6 to 0.8 | 0 | 0 | 0.38 |
| | 0.8 to 1.0 | 0 | 0 | 0 |
| | M > 1.0 | 0 | 0 | 0 |
| $10^\circ \leqq \alpha \leqq 20^\circ$ | M < 0.4 | 2.42 | 0.38 | 12.83 |
| | 0.4 to 0.6 | 1.66 | 0.75 | 4.99 |
| | 0.6 to 0.8 | 0.48 | 0.70 | 0.59 |
| | 0.8 to 1.0 | 0.16 | 0.21 | 0.38 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 0.38 | 0.32 | 38.11 |
| | 0.4 to 0.6 | 3.17 | 0.48 | 15.51 |
| | 0.6 to 0.8 | 0.59 | 0.27 | 1.61 |
| | 0.8 to 1.0 | 0.27 | 0.21 | 0.64 |
| | M > 1.0 | 0 | 0 | 0 |

TABLE 17.- PERCENT OF TOA (44.3 SECONDS) WITHIN THRUST VECTORING INTERVALS FOR PILOT GROUP 2

| Angle of attack | Mach number | Percent of TOA within – | | |
|---|---|---|---|---|
| | | $0^\circ \leqq \theta_j < 10^\circ$ | $10^\circ \leqq \theta_j \leqq 20^\circ$ | $20^\circ < \theta_j \leqq 30^\circ$ |
| $\alpha < 10^\circ$ | M < 0.4 | 7.20 | 0.33 | 8.09 |
| | 0.4 to 0.6 | 6.07 | 0.05 | 3.95 |
| | 0.6 to 0.8 | 3.25 | 0 | 0 |
| | 0.8 to 1.0 | 0.38 | 0 | 0 |
| | M > 1.0 | 0 | 0 | 0 |
| $10^\circ \leqq \alpha \leqq 20^\circ$ | M < 0.4 | 2.73 | 0.14 | 9.83 |
| | 0.4 to 0.6 | 7.38 | 0.19 | 10.16 |
| | 0.6 to 0.8 | 2.68 | 0 | 0.75 |
| | 0.8 to 1.0 | 1.32 | 0 | 0.09 |
| | M > 1.0 | 0 | 0 | 0 |
| $\alpha > 20^\circ$ | M < 0.4 | 1.22 | 0.14 | 8.89 |
| | 0.4 to 0.6 | 6.49 | 0.80 | 12.42 |
| | 0.6 to 0.8 | 2.59 | 0.24 | 1.83 |
| | 0.8 to 1.0 | 0.80 | 0 | 0 |
| | M > 1.0 | 0 | 0 | 0 |

[redacted]

### Combined Results

Figure 18 shows the TOA at 180 seconds, average AML value, and probability of conversion for the five cases studied with the data from both pilot groups combined. All three parameters indicate the general results: (1) The hypothetical opponent could decisively defeat the basic F-4 in the one-on-one ACM situation, (2) vectoring alone improved the F-4 maneuvering capability somewhat, and (3) vectoring plus induced lift improved the F-4 maneuverability to the point at which it was almost equal to the opponent.

## CORRELATION OF RESULTS

### Aircraft Maneuvering Parameter (AMP)

One of the objectives of the previous studies has been to develop a function relating a scoring parameter, such as TOA, to aircraft capability. Such a function would make it possible to predict ACM outcome from basic aircraft characteristics. One such function being examined is the aircraft maneuvering parameter (AMP) described in reference 11, which relates TOA to the basic characteristics $\left(T/W,\ W/S,\ C_{L,max},\ \text{and}\ L/D\right)$ of each aircraft.

The aircraft maneuvering parameter is used in the following manner:

(1) An AMP value is computed for each aircraft by

$$\mathrm{AMP} = \frac{\left[(T/W)(L/D)_{man}\right]^{1/3} C_{L,max}}{W/S}$$

where all conditions are referenced to $M = 0.8$ at an altitude of 3048 meters (10 000 feet). The lift-drag ratio at maneuver conditions $(L/D)_{man}$ is assumed to be one-half $(L/D)_{max}$. Thrust vectoring capability is treated as an increase in $C_{L,max}$.

(2) The AMP ratio for each pair of competing aircraft is then computed. The AMP ratio for a particular aircraft is the AMP value of that aircraft divided by the AMP value of the opponent. The AMP ratio of the opponent is the inverse. Thus, as one aircraft is improved the AMP ratio for the improved aircraft increases and simultaneously the AMP ratio for the opponent decreases. The AMP ratios for the aircraft in the five cases studied are given in table 18.

(3) After the AMP ratios are determined, the nondimensional time on offense with advantage TOA/t can be predicted by using the curve in figure 19. The ratio TOA/t is the total TOA normalized by the total time of the engagement (t = 180 sec). The curve in figure 19 is based on a correlation of results from previous studies discussed in reference 11.

[redacted]

[redacted]

TABLE 18.- AMP RATIOS FOR SIMULATED AIRCRAFT

| Case | Aircraft | | AMP ratio | |
|---|---|---|---|---|
| | A | B | A/B | B/A |
| 1 | Basic F-4 | Basic F-4 | 1.000 | 1.000 |
| 2 | Basic F-4 | HMA | .860 | 1.163 |
| 3 | Thrust vectoring only | Basic F-4 | 1.041 | .961 |
| 4 | Thrust vectoring plus induced lift | Basic F-4 | 1.081 | .925 |
| 5 | Thrust vectoring plus induced lift | HMA | .930 | 1.075 |

The points plotted in figure 19 show the results from the five cases studied. The results are in satisfactory agreement with the predicted results; but matching would not be expected because of differences in pilots and aircraft flying qualities. As noted in reference 11, however, results of previous studies involving parametric changes in similar aircraft, and simulated engagements between dissimilar aircraft, have agreed well with AMP.

## Correlation of Scoring Parameters

If a correlation can be established between scoring parameters such as TOA, AML value, and time to convert, the usefulness of prediction parameters such as AMP would be further increased. Therefore, possible direct (linear) correlation of the DMS scoring parameters was tested using the correlation coefficient $r$ (ref. 12), where $|r| = 1$ implies linear correlation and $r = 0$ implies no correlation. The correlation coefficient was computed for each of the five scoring parameters by using the average over 24 runs as a data point, giving four data points each (two cockpits and two pilot groups) for cases 1, 2, 4, and 5 and two data points (one pilot group) for case 3, by

$$r = \frac{\sum_{i=1}^{18}\left[(\bar{x} - x_i)(\bar{y} - y_i)\right]}{\sqrt{\left[\sum_{i=1}^{18}(\bar{x} - x_i)^2\right]\left[\sum_{i=1}^{18}(\bar{y} - y_i)^2\right]}}$$



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and $\bar{x}$ and $\bar{y}$ are the means over all cases and $x_i$ is the mean over 24 runs where

$$\bar{x} = \frac{1}{18} \sum_{i=1}^{18} x_i \qquad \bar{y} = \frac{1}{18} \sum_{i=1}^{18} y_i$$

The correlation coefficients obtained are given in table 19. Average time to convert was not analyzed because in some runs no conversions occurred; therefore, no time to convert could be assessed.

TABLE 19.- CORRELATION COEFFICIENTS BETWEEN SCORING PARAMETERS

| Parameters | r |
|---|---|
| Average TOA at 180 sec vs probability of conversion . . . . | 0.900 |
| Average TOA at 180 sec vs time in envelope . . . . . . . . . | 0.867 |
| Average TOA at 180 sec vs AML value . . . . . . . . . . . . | 0.948 |
| Probability of conversion vs average time in envelope . . . . | 0.838 |
| Probability of conversion vs average AML value . . . . . . . | 0.860 |
| Average time in envelope vs AML value . . . . . . . . . . . | 0.806 |

Table 19 indicates that all four scoring parameters are linearly correlated, with TOA providing the best correlation. This good correlation provides confidence in using these measures of performance with prediction models such as AMP.

## CONCLUDING REMARKS

A simulation study of the effects on fighter maneuverability of limited thrust vectoring with and without induced lift has been made. Limited ($0^{\circ}$ to $30^{\circ}$) thrust vectoring, simulated without a weight or thrust penalty, improved the maneuverability of the simulated F-4 aircraft. The inclusion of an additional force representing induced lift due to thrust vectoring further improved the F-4's maneuverability.

Most of the run time in simulated engagements was spent at speeds below $M = 0.6$. Pilots used thrust vectoring extensively at these speeds, where it improved the sustained and instantaneous (maximum) turn rate capability. Pilots used thrust vectoring a smaller percent of the time at speeds above $M = 0.6$. At these higher speeds thrust vectoring resulted in rapid deceleration and poorer sustained turning capability. Pilots learned quickly to use thrust vectoring, and asked about the possibility of implementing an automatic thrust vectoring logic.

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Several of the parameters used to score or compare the results of the simulation were shown to be highly correlated. This suggests that a parameter such as the aircraft maneuvering parameter (AMP) which relates one scoring parameter (time on offense with advantage) to the aircraft configuration can also relate other scoring parameters to the aircraft configuration.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., March 3, 1975.

[redacted]

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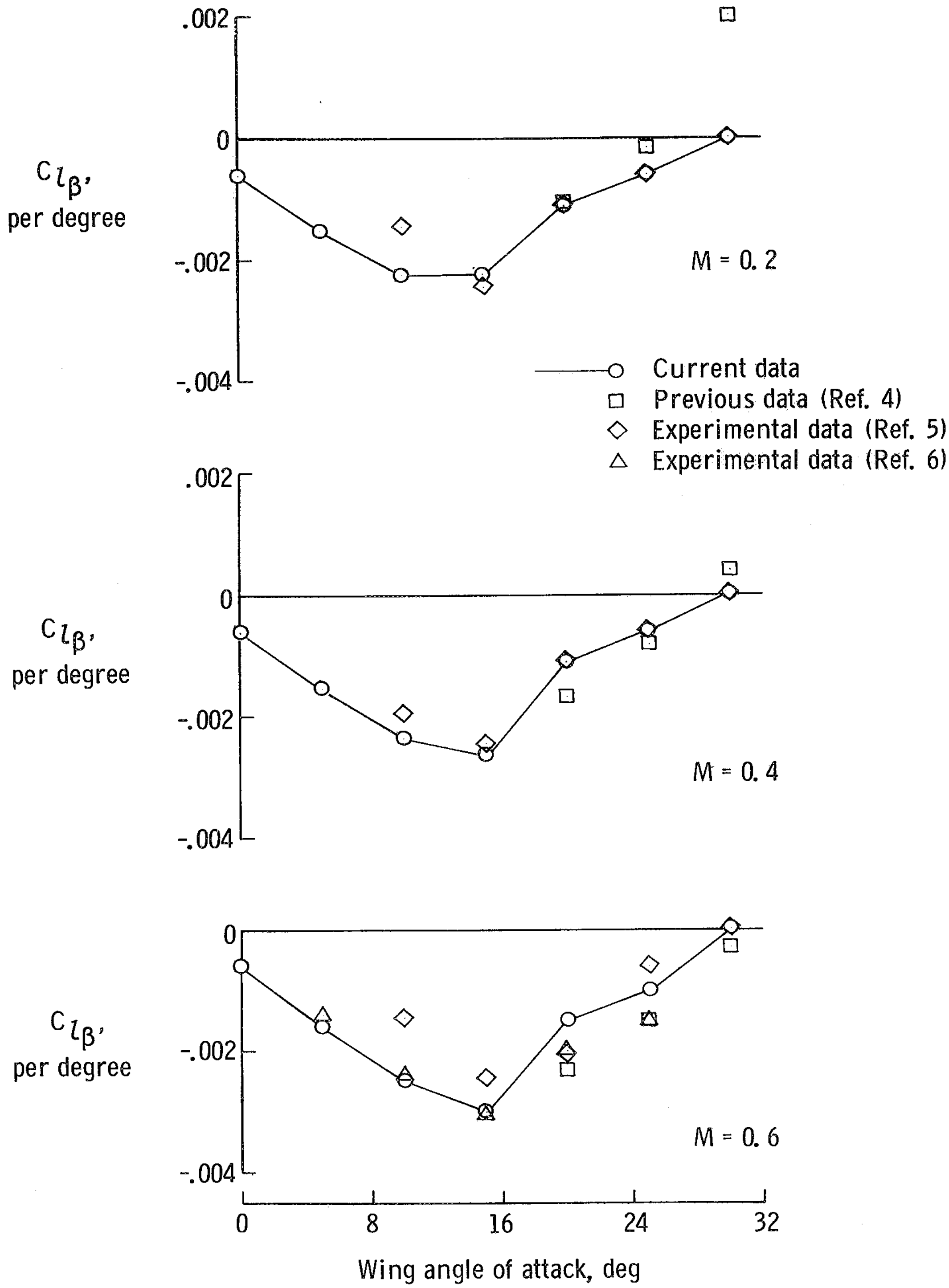


Figure 1.- Rolling-moment derivative with respect to sideslip angle at altitude of 4572 m (15 000 ft).

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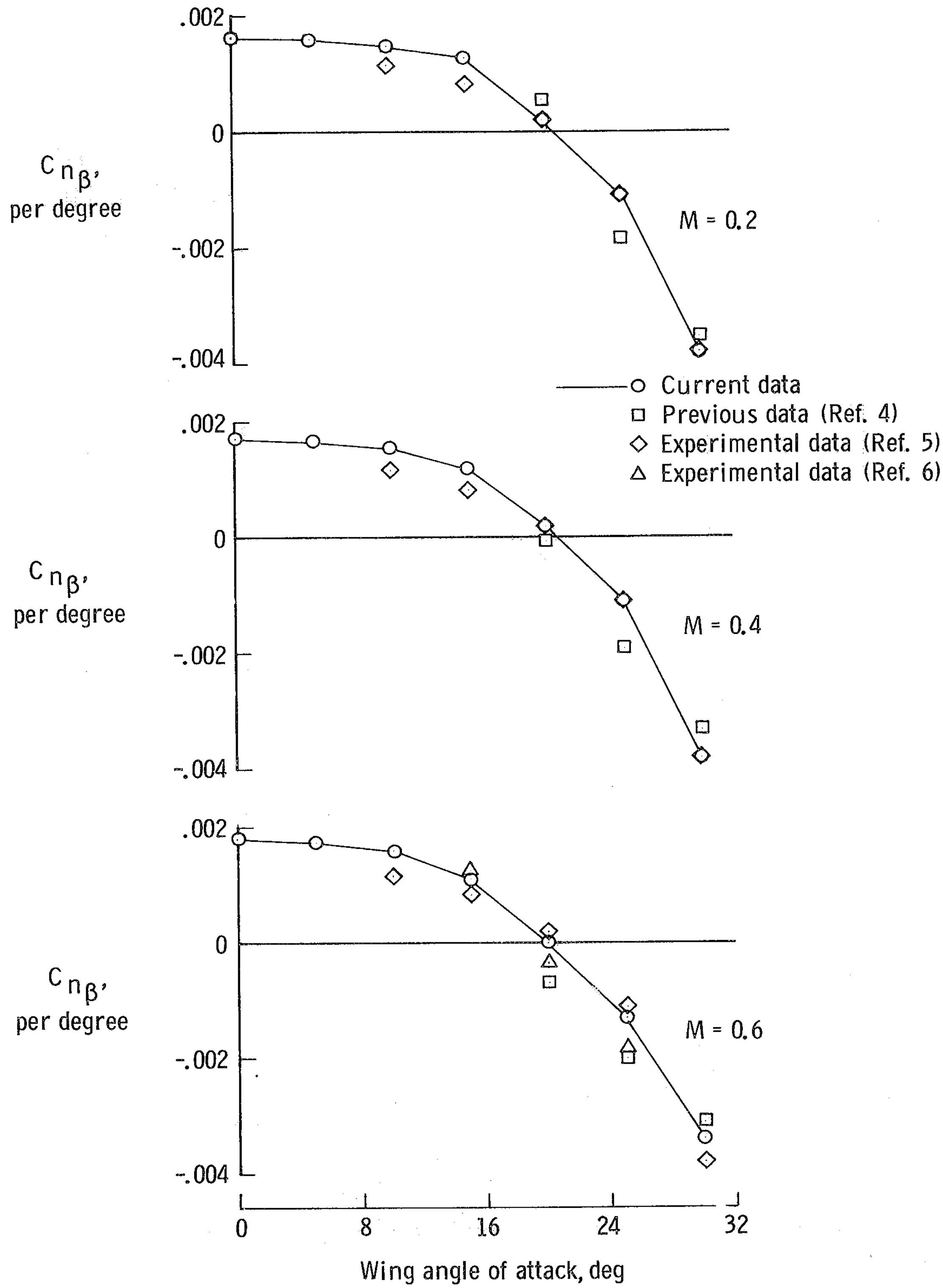


Figure 2.- Yawing-moment derivative with respect to sideslip angle at altitude of 4572 m (15 000 ft).

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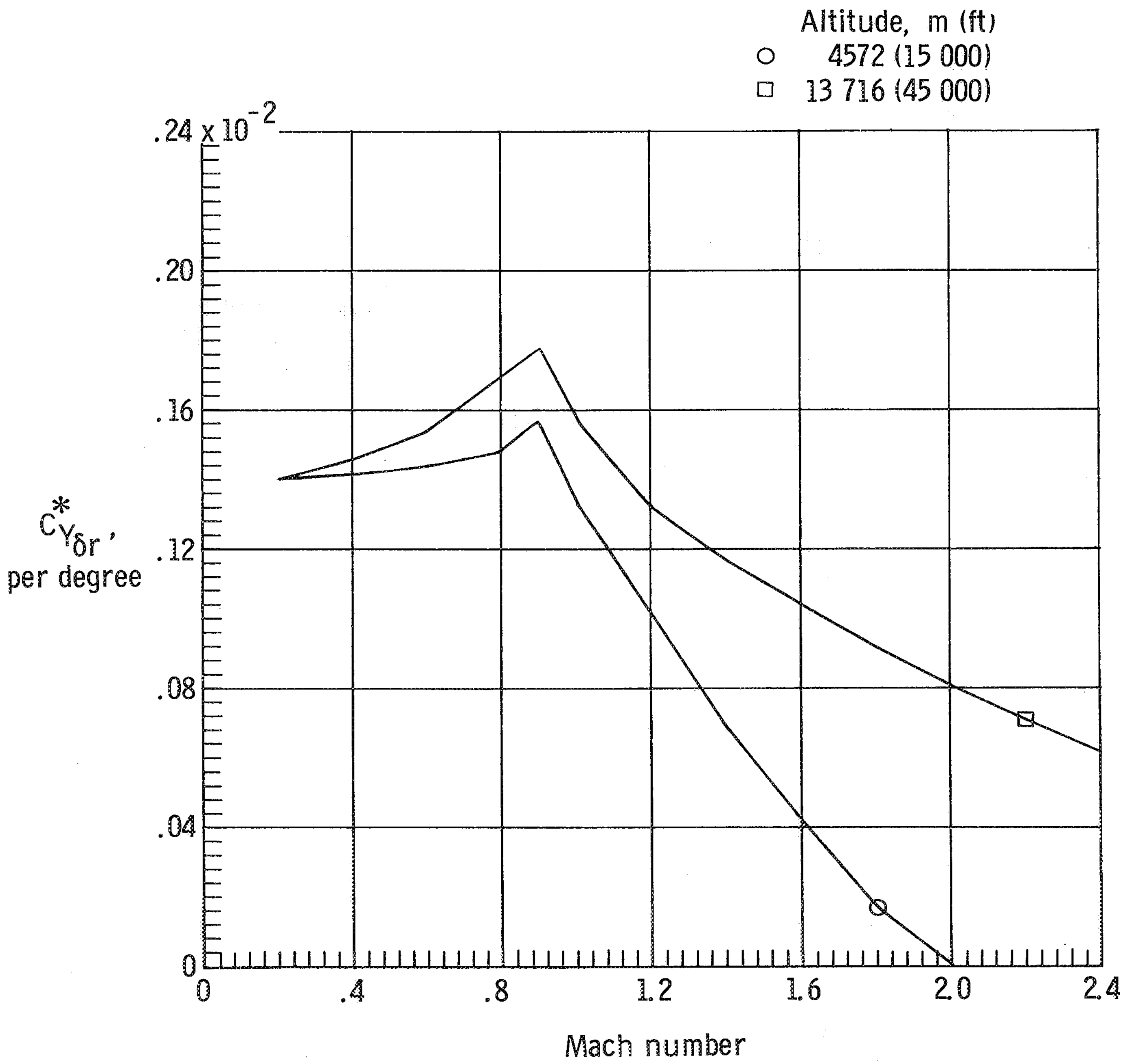


Figure 3.- Lateral-force coefficient derivative with respect to rudder deflection.

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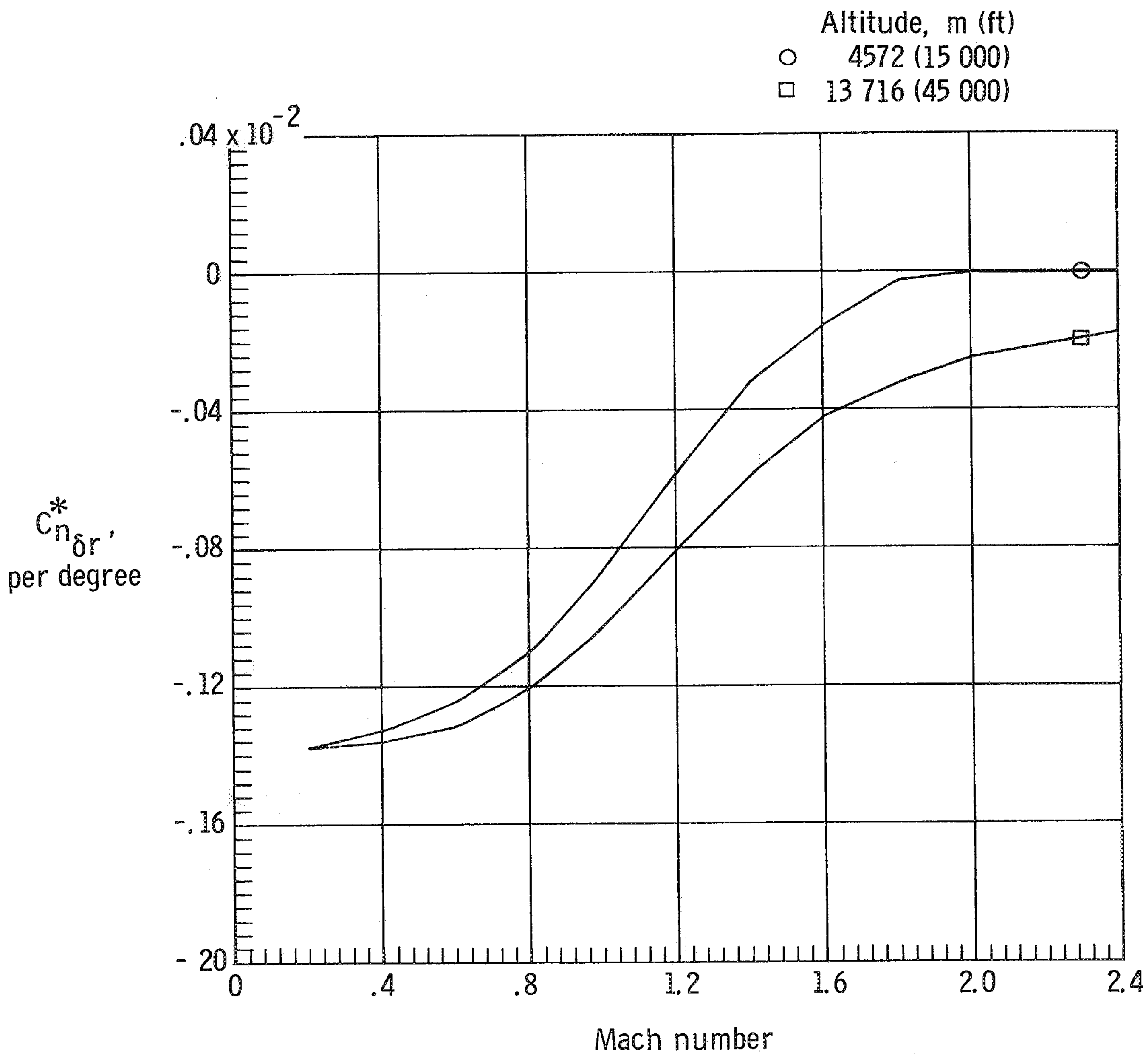


Figure 4.- Yawing-moment derivative with respect to rudder deflection.

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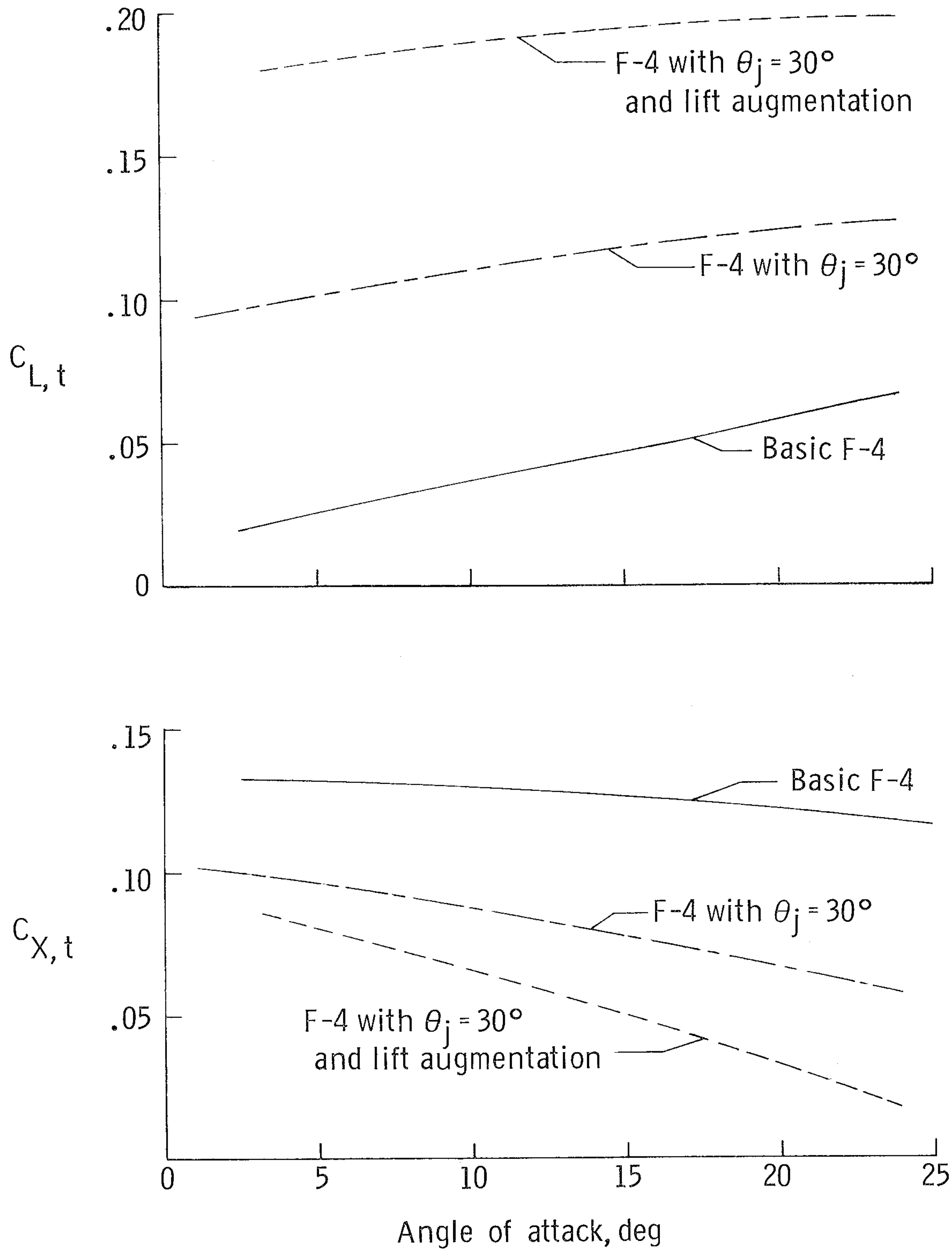


(a) $C_{L,t}$ and $C_{X,t}$ as a function of $\alpha$.

Figure 5.- Normal and longitudinal thrust coefficient for simulated aircraft at $M = 0.6$ and altitude of 3048 m (10 000 ft).



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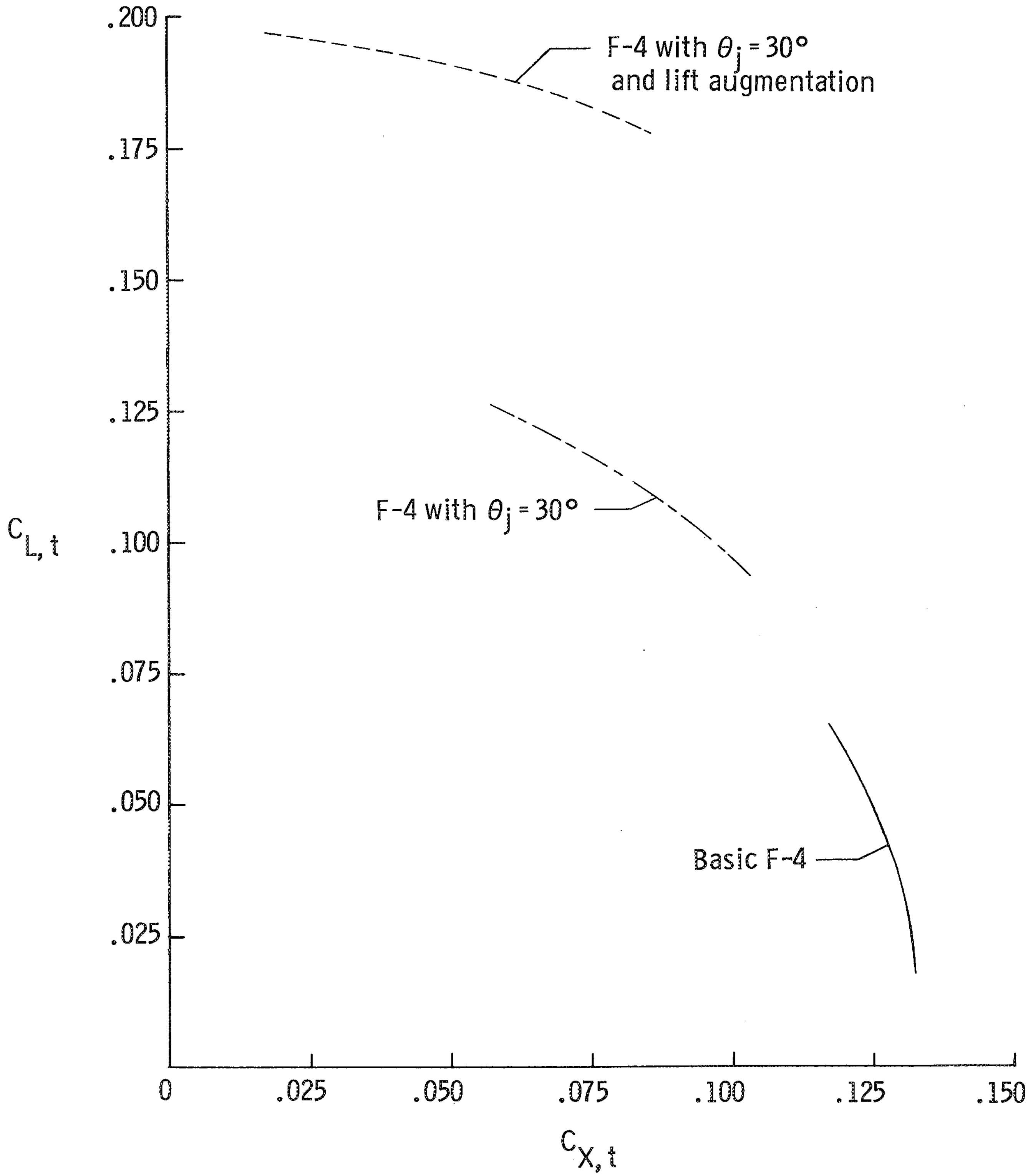



(b) $C_{L,t}$ as a function of $C_{X,t}$.

Figure 5.- Concluded.

[redacted]

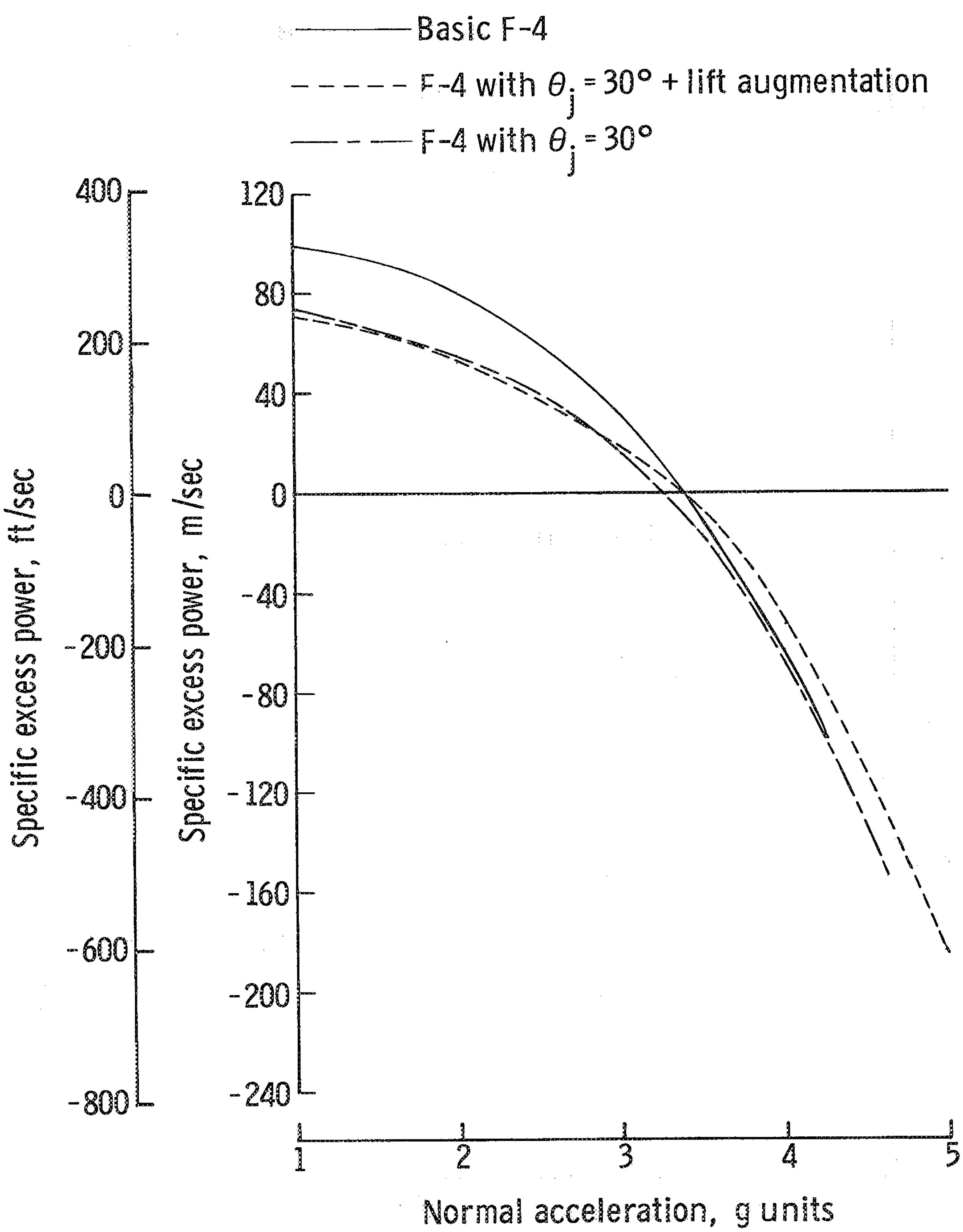
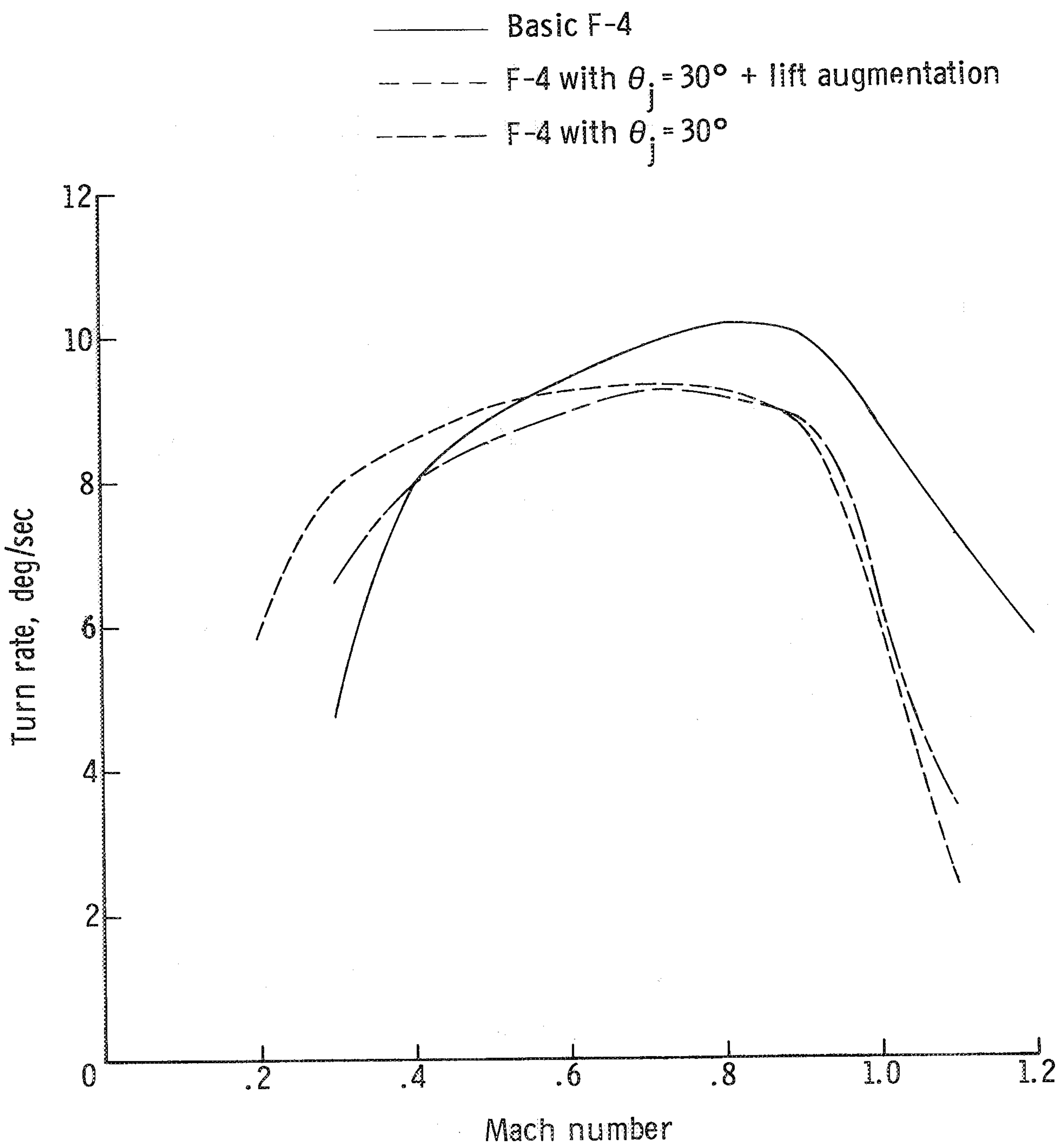



Figure 6.- Specific excess power.

[redacted]

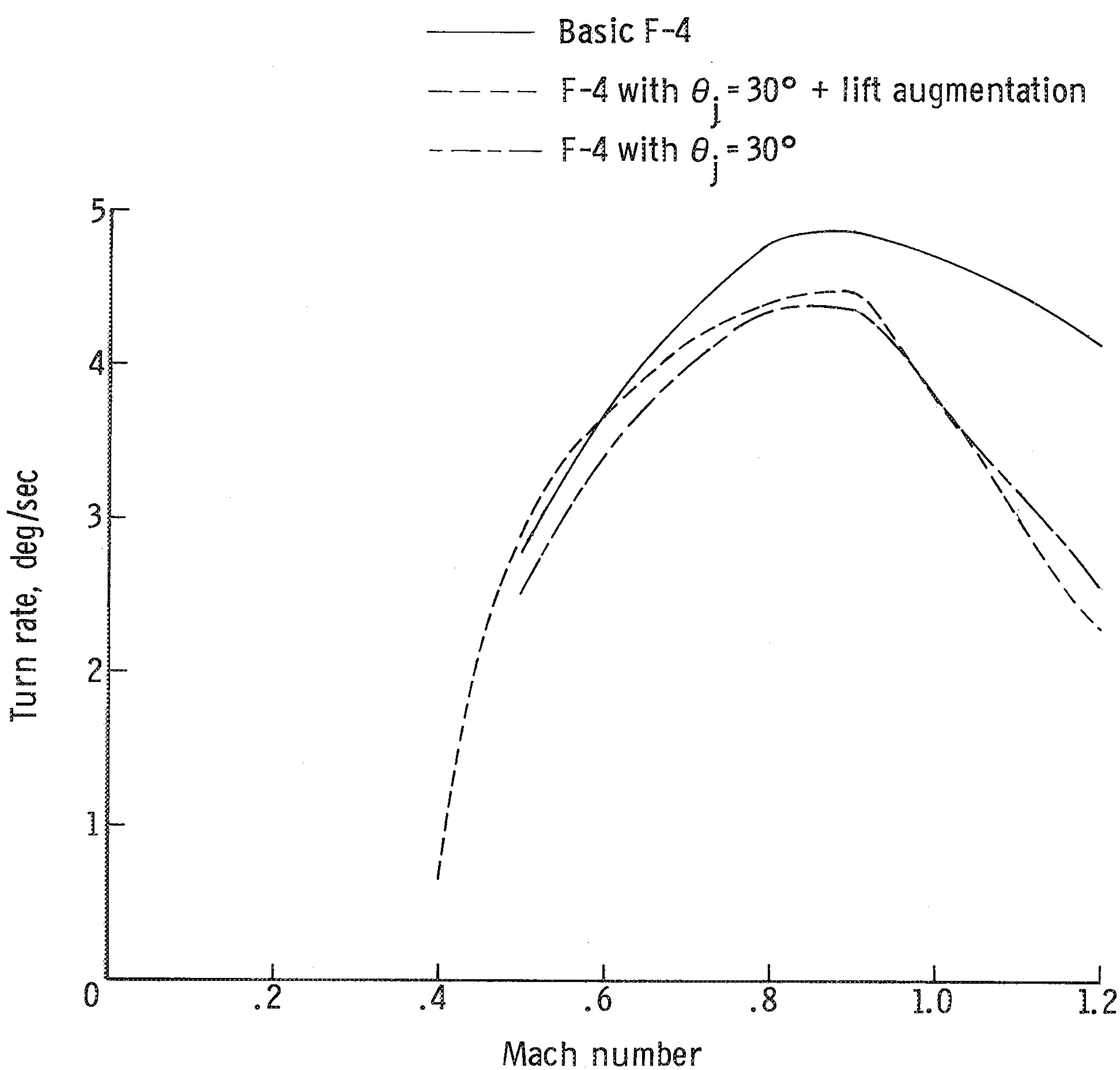



(a) Altitude, 3048 m (10 000 ft).

Figure 7.- Sustained horizontal turn rate.

[redacted]

[redacted]




(b) Altitude, 9144 m (30 000 ft).

Figure 7.- Concluded.



[redacted]

[redacted]

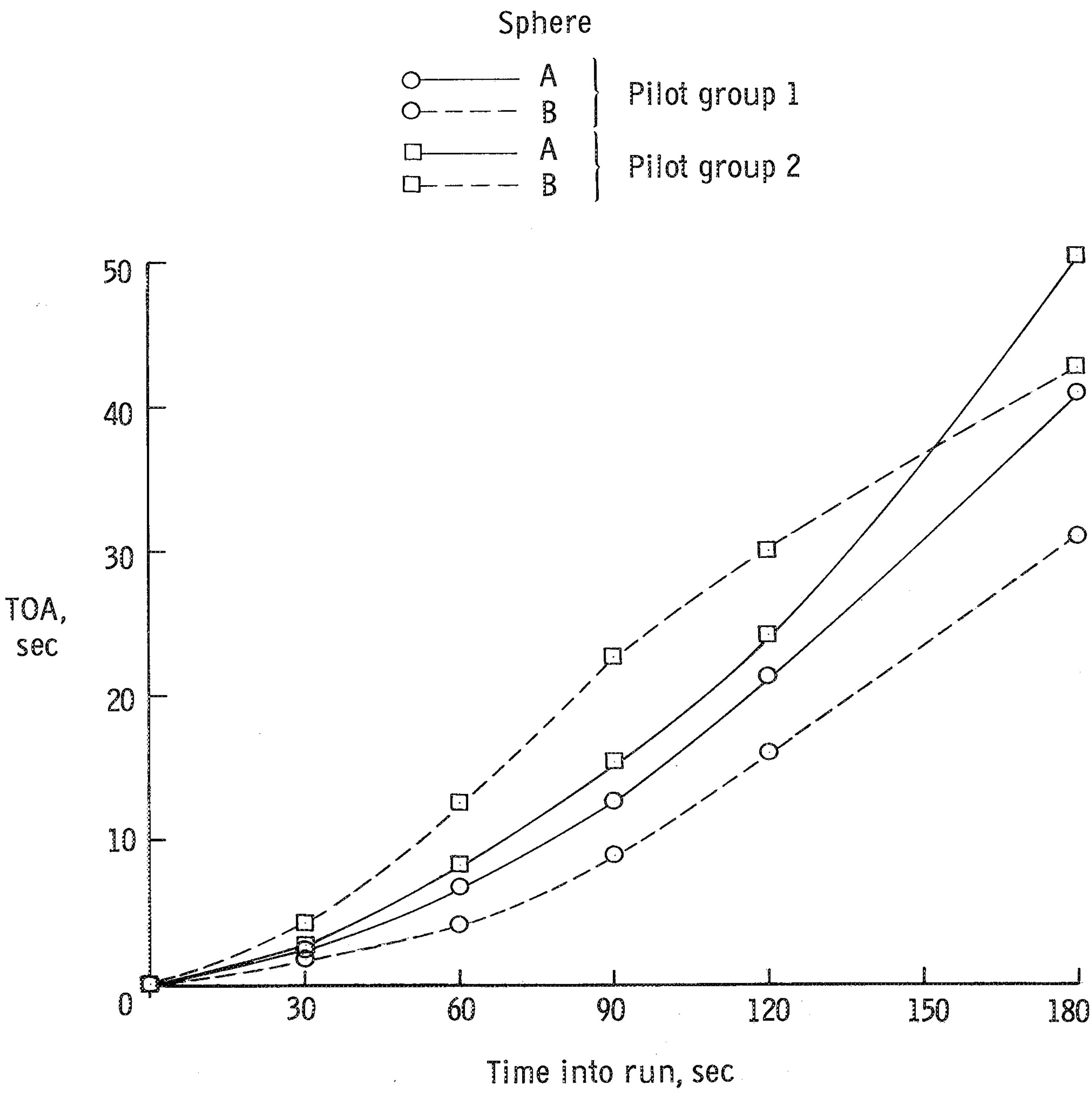



Figure 8. - Average TOA for equal aircraft.

[redacted]

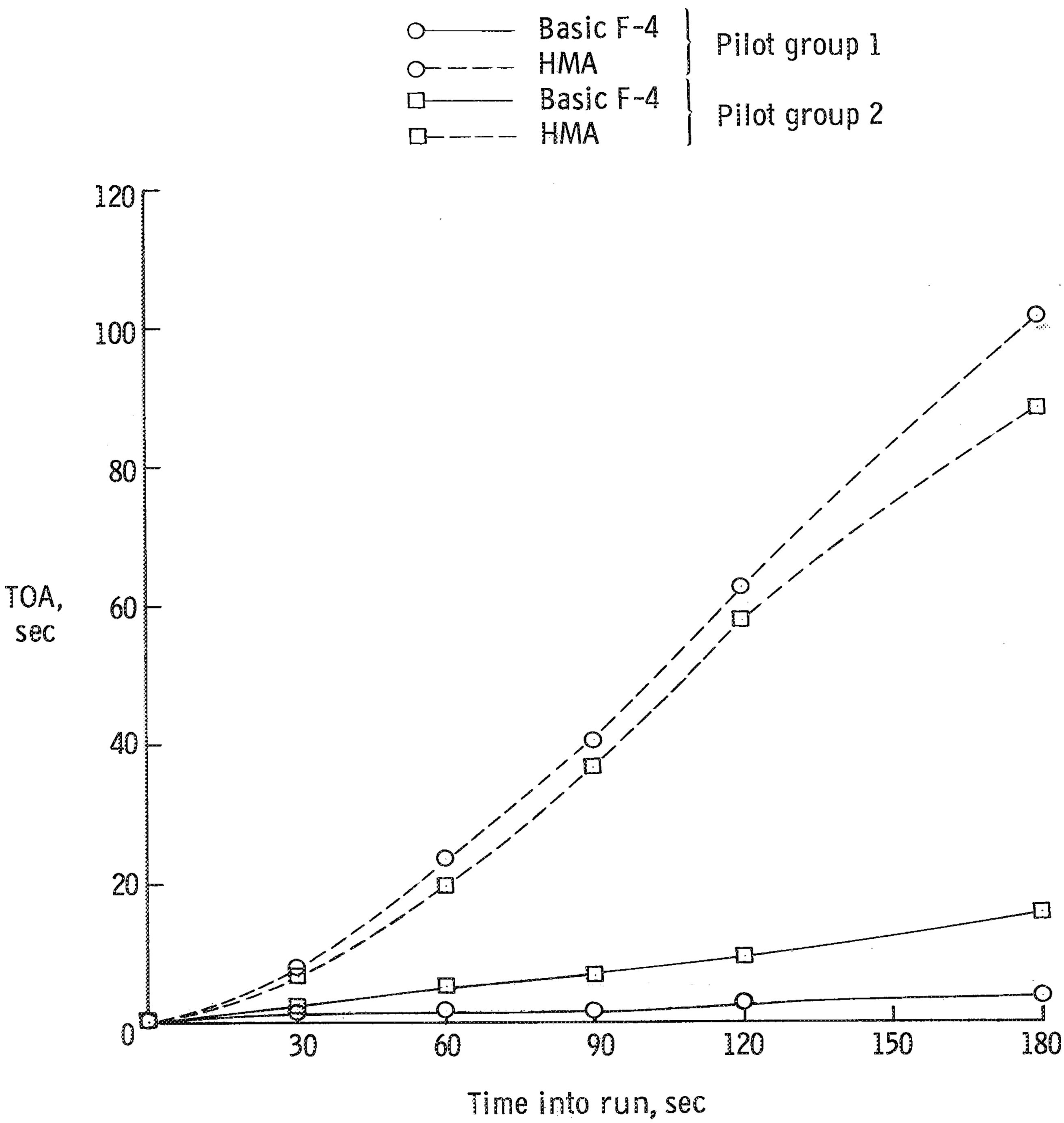



Figure 9.- Average TOA for basic F-4 flown against HMA.

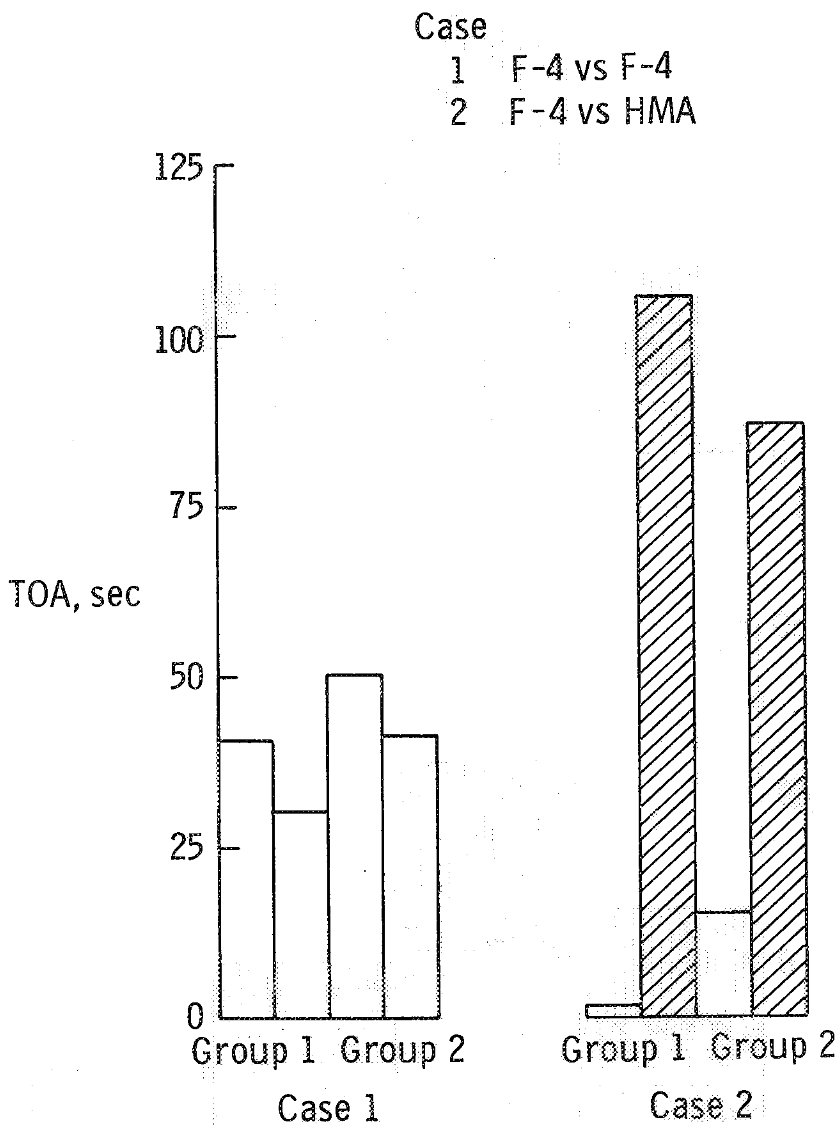



Figure 10.- Average TOA at 180 seconds.

[redacted]

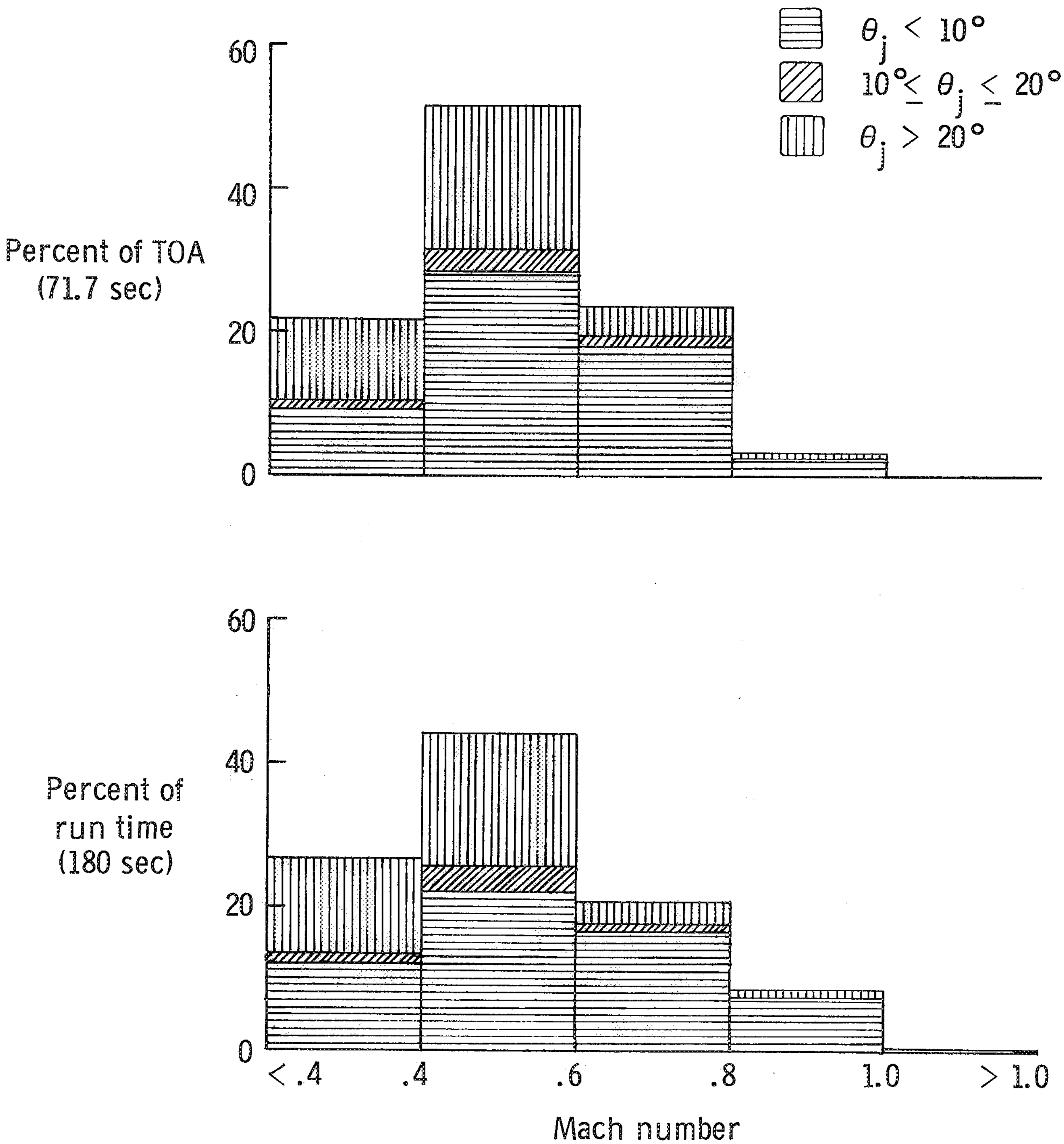



Figure 11.- Percent of run time and TOA in intervals of Mach number and thrust vector angle. Case 3.



[redacted]

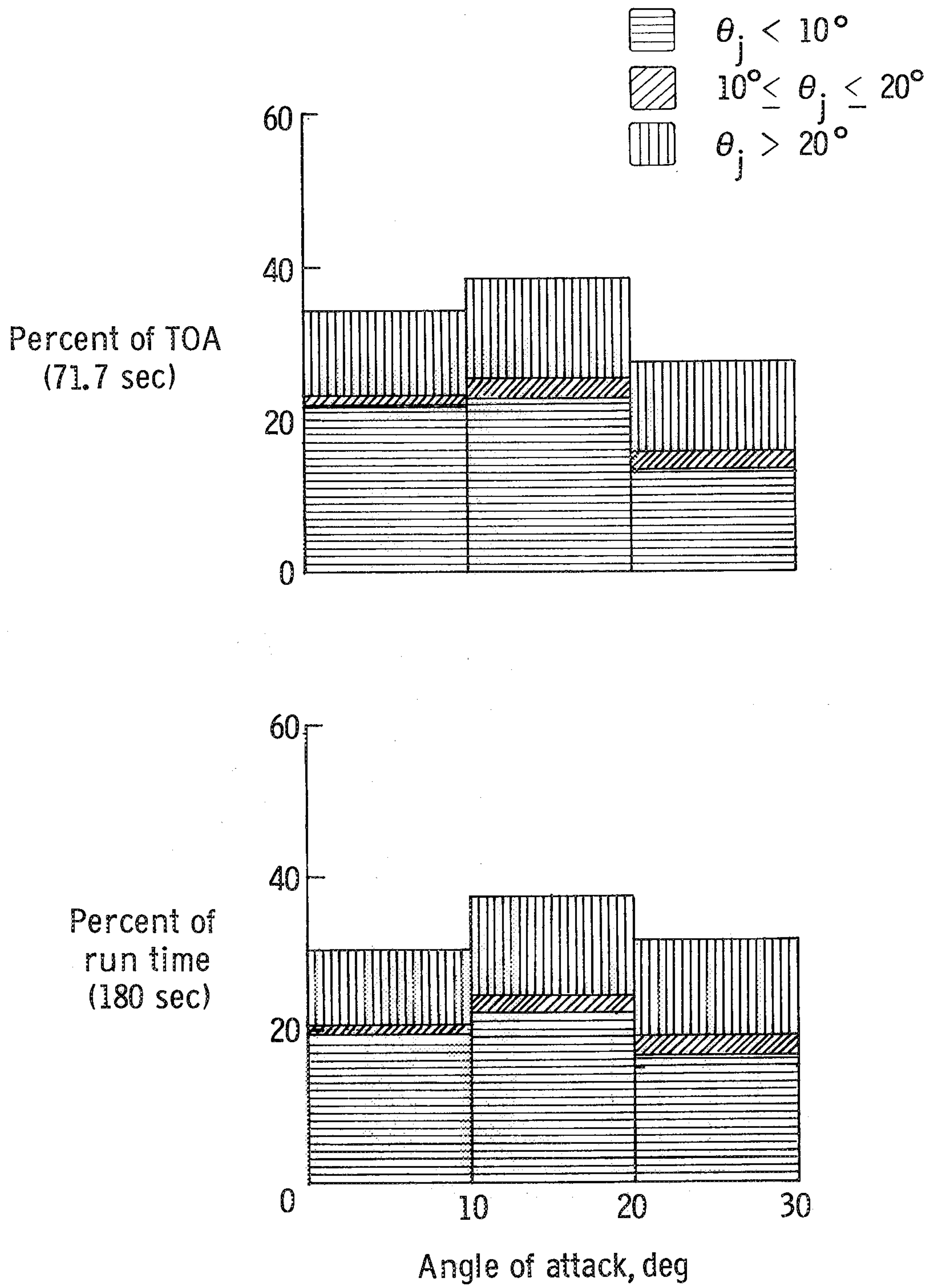



Figure 12.- Percent of run time and TOA in angle-of-attack regions and intervals of thrust vector angle. Case 3.

[redacted]

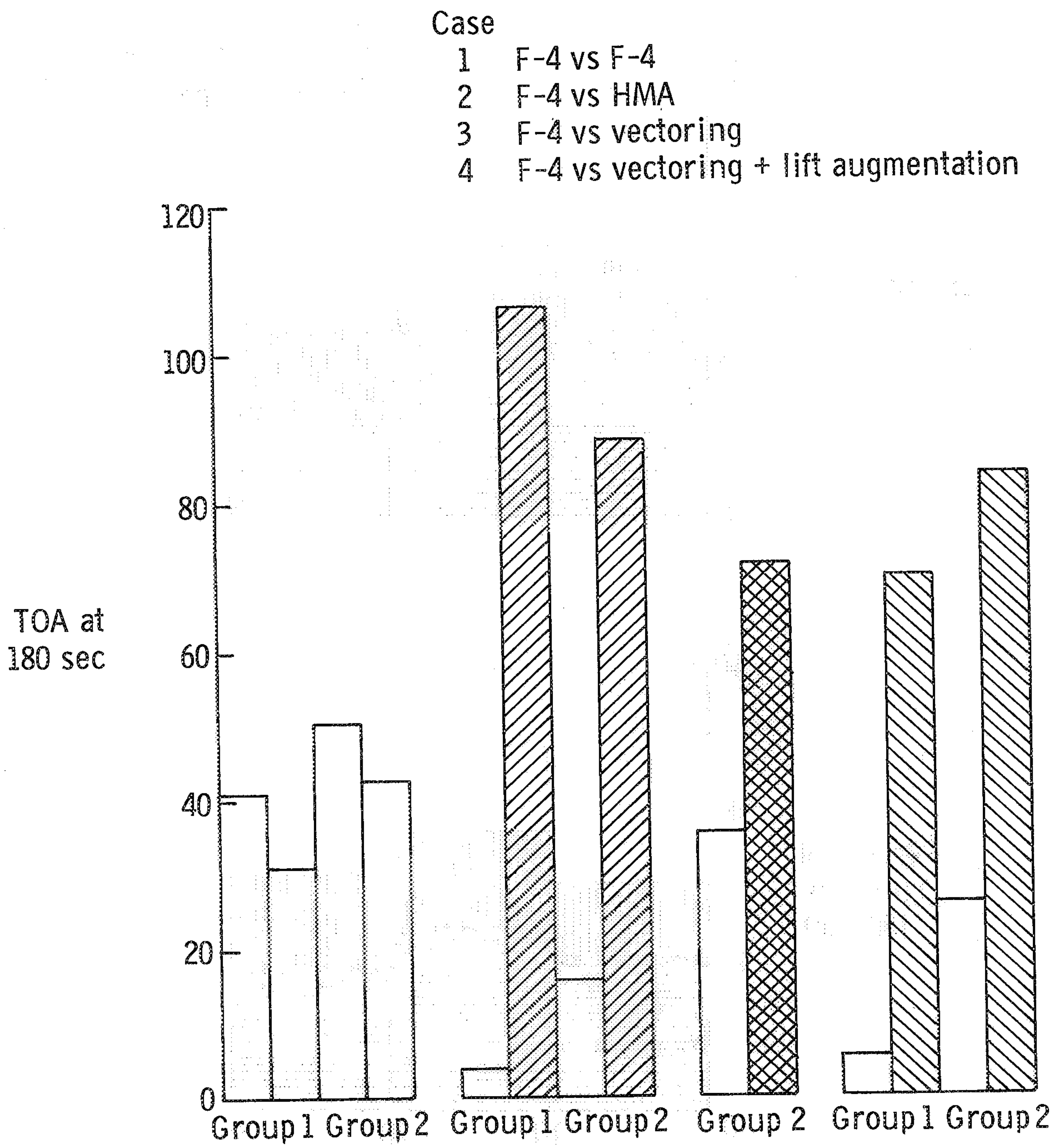
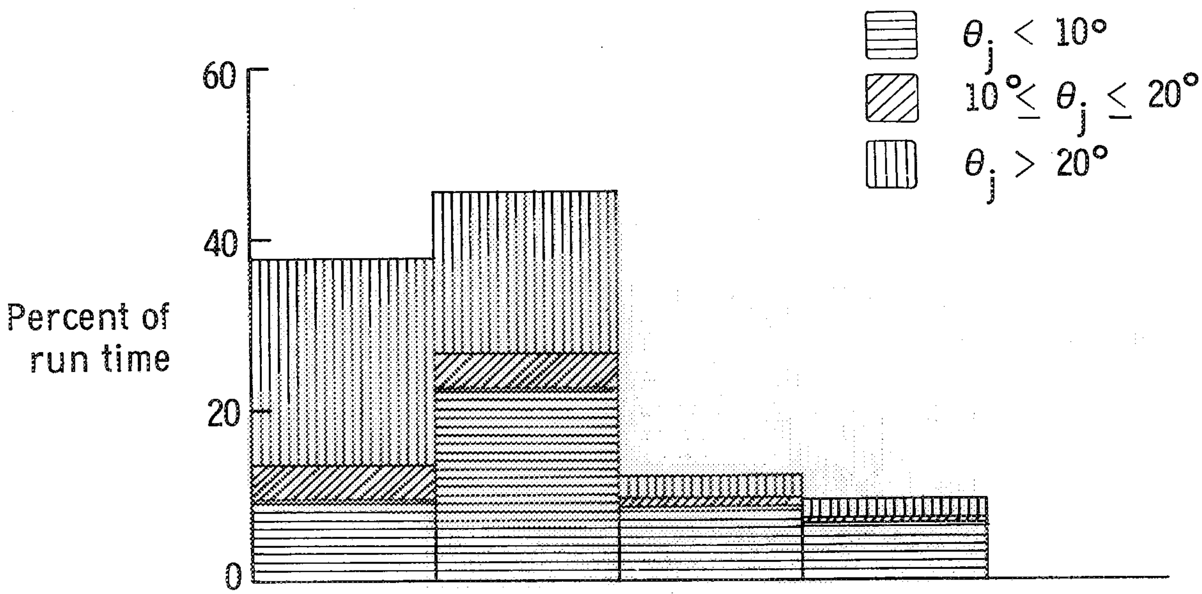


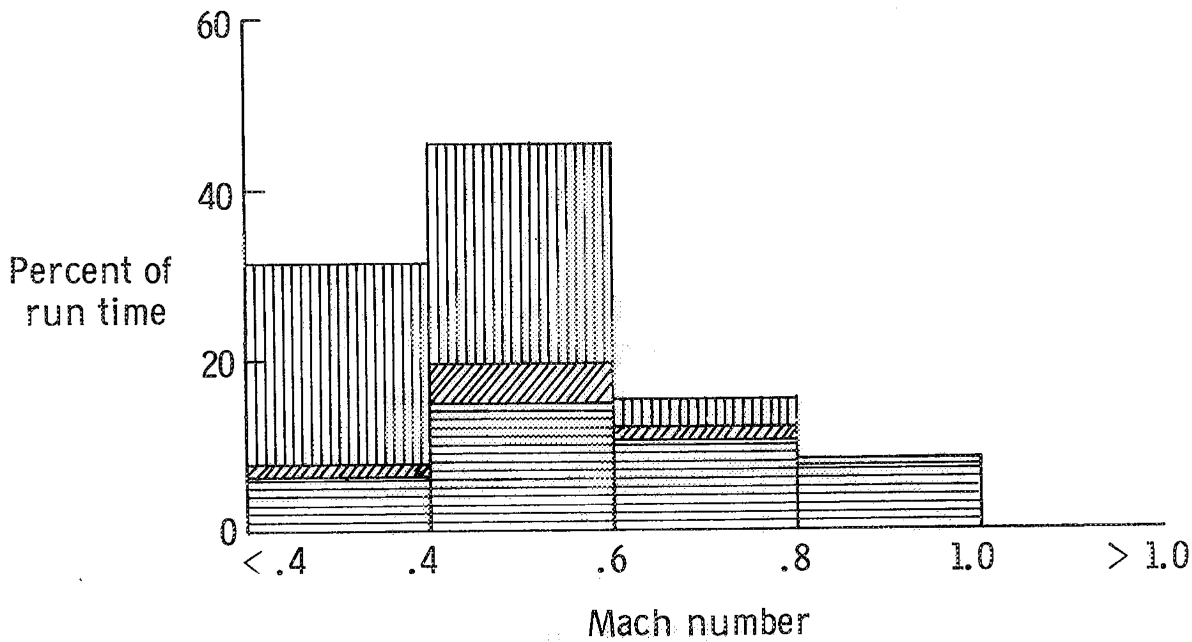

Figure 13.- Summary of TOA at 180 seconds.



[redacted]



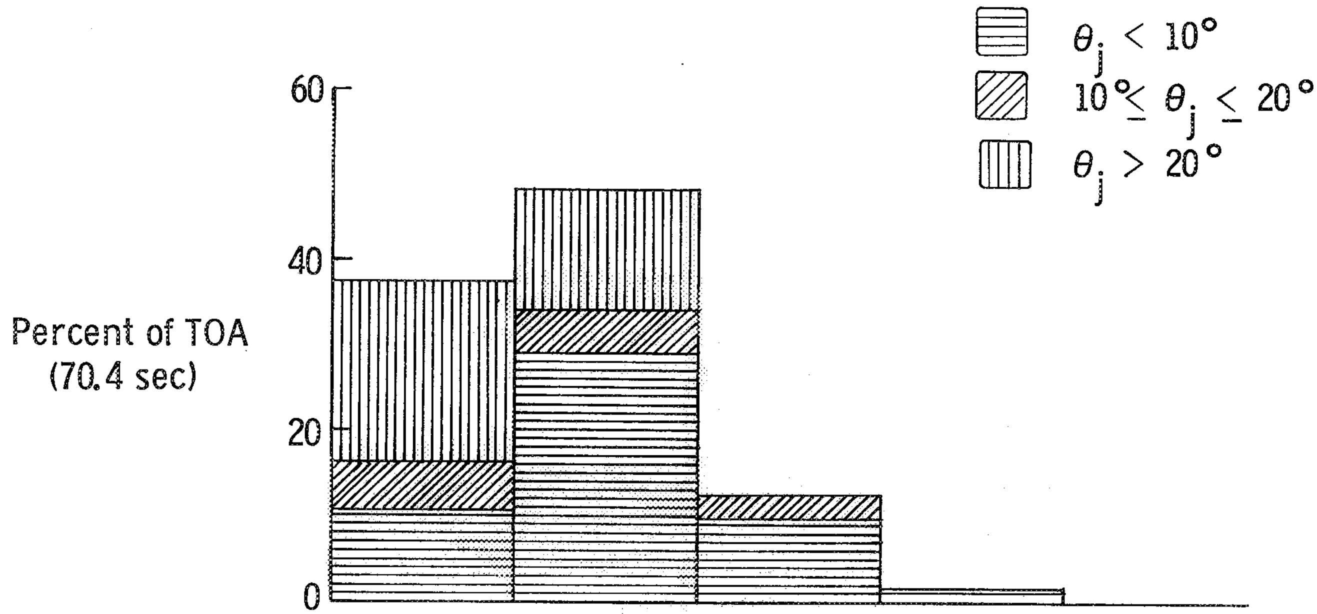

(a) Pilot group 1.



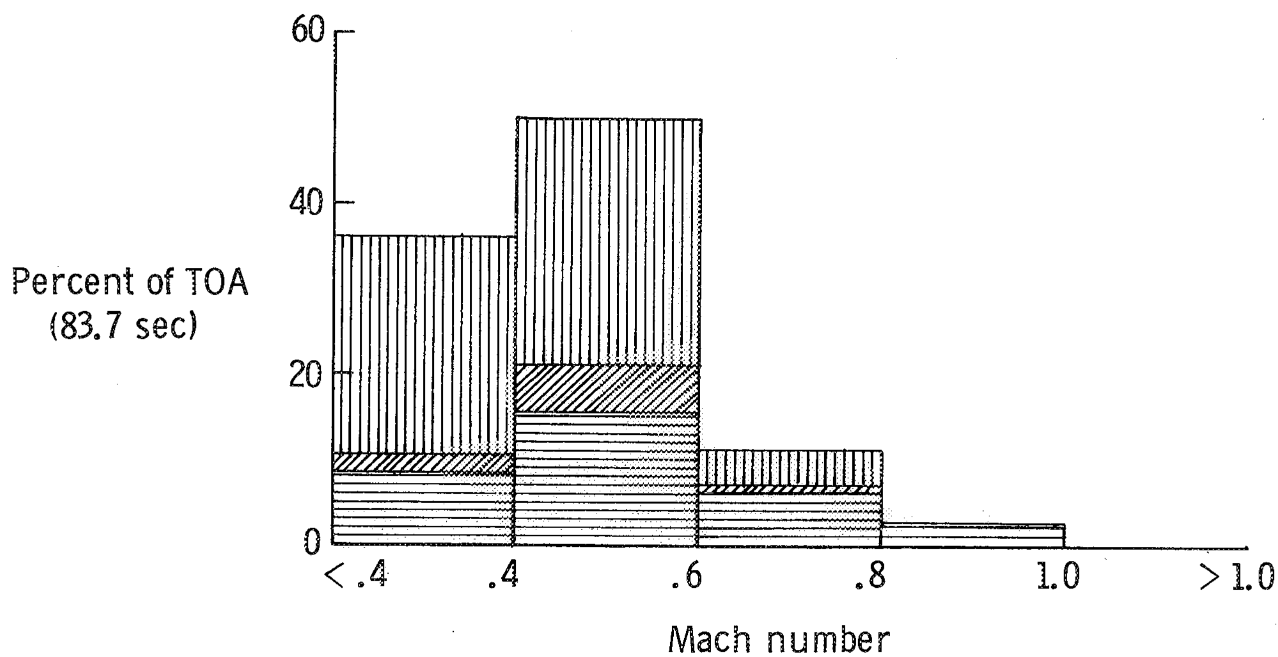

(b) Pilot group 2.

Figure 14.- Percent of run time in intervals of Mach number and thrust vector angle. Case 4.

[redacted]




(a) Pilot group 1.



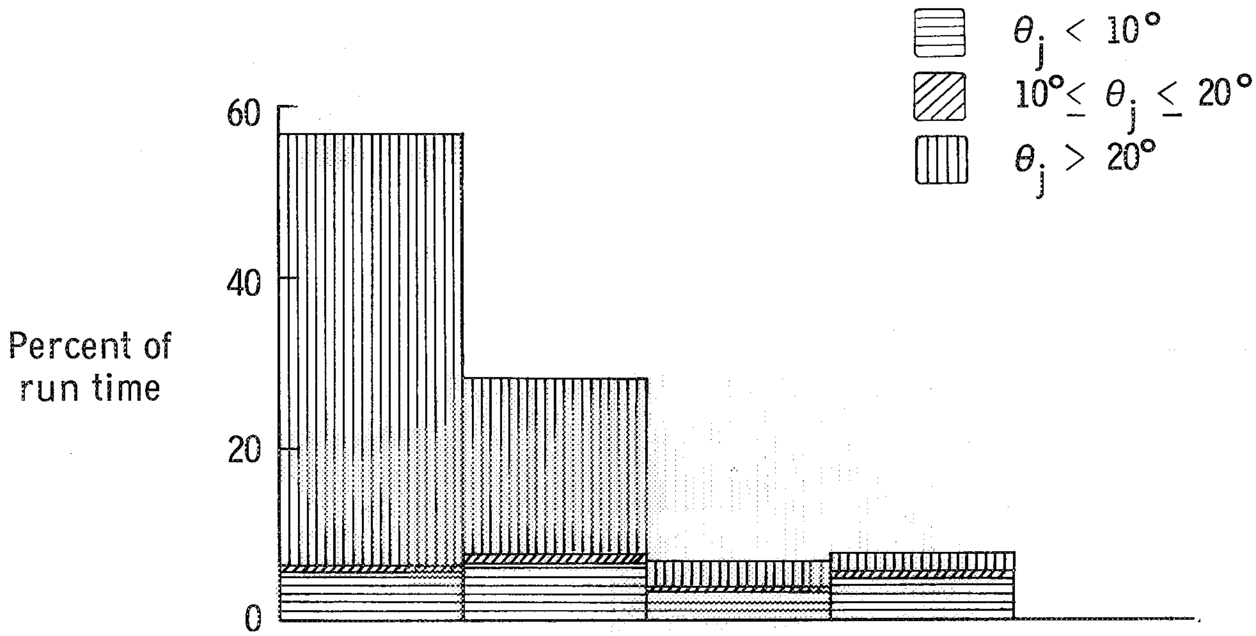

(b) Pilot group 2.

Figure 15.- Percent of TOA in intervals of Mach number and thrust vector angle. Case 4.

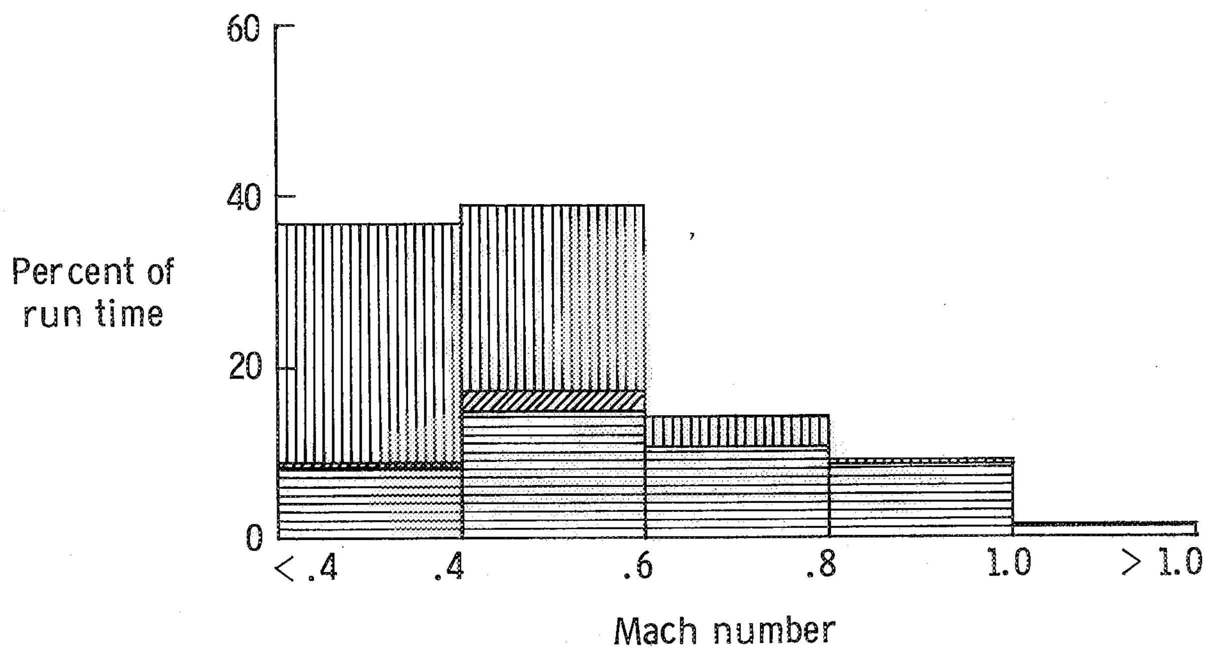


[redacted]

[redacted]



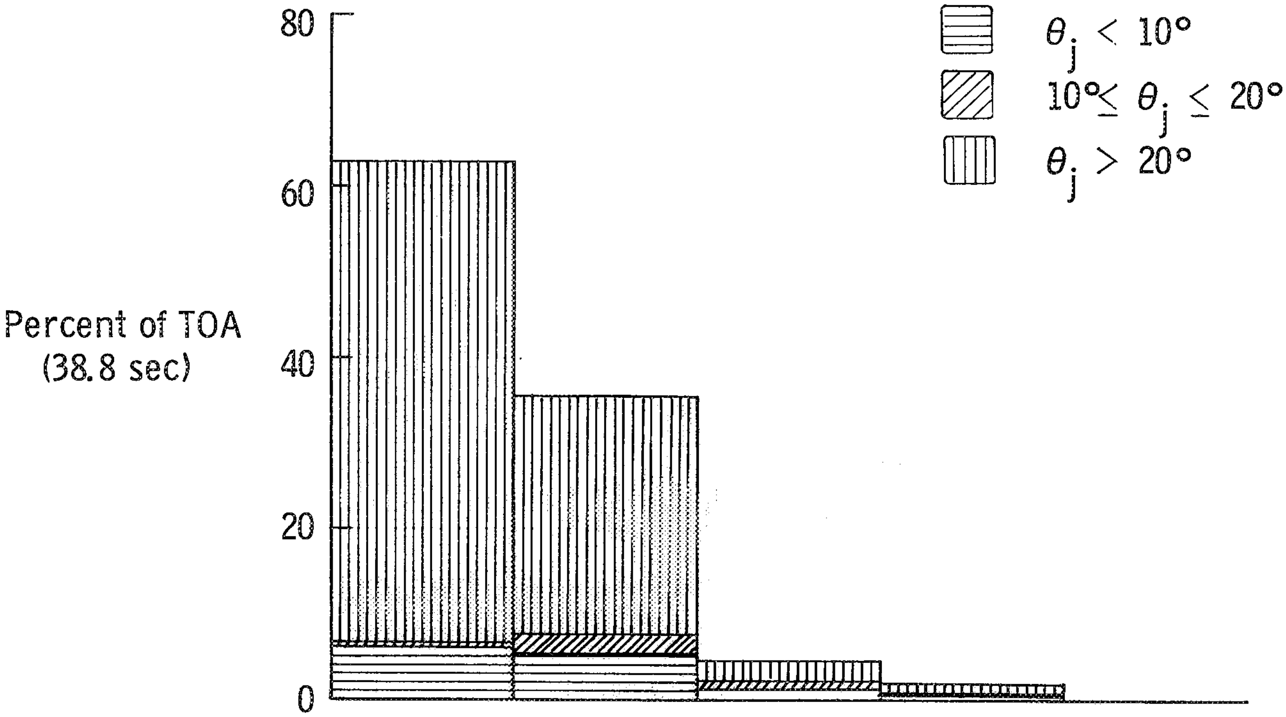

(a) Pilot group 1.



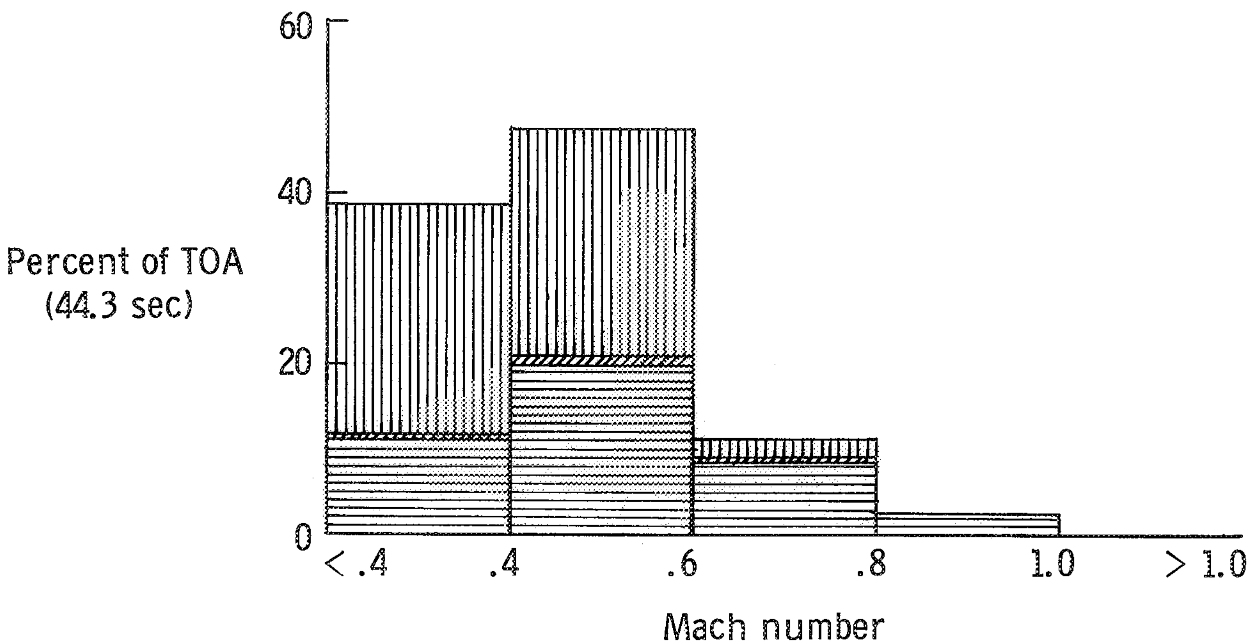

(b) Pilot group 2.

Figure 16.- Percent of run time in intervals of Mach number and thrust vector angle. Case 5.

[redacted]



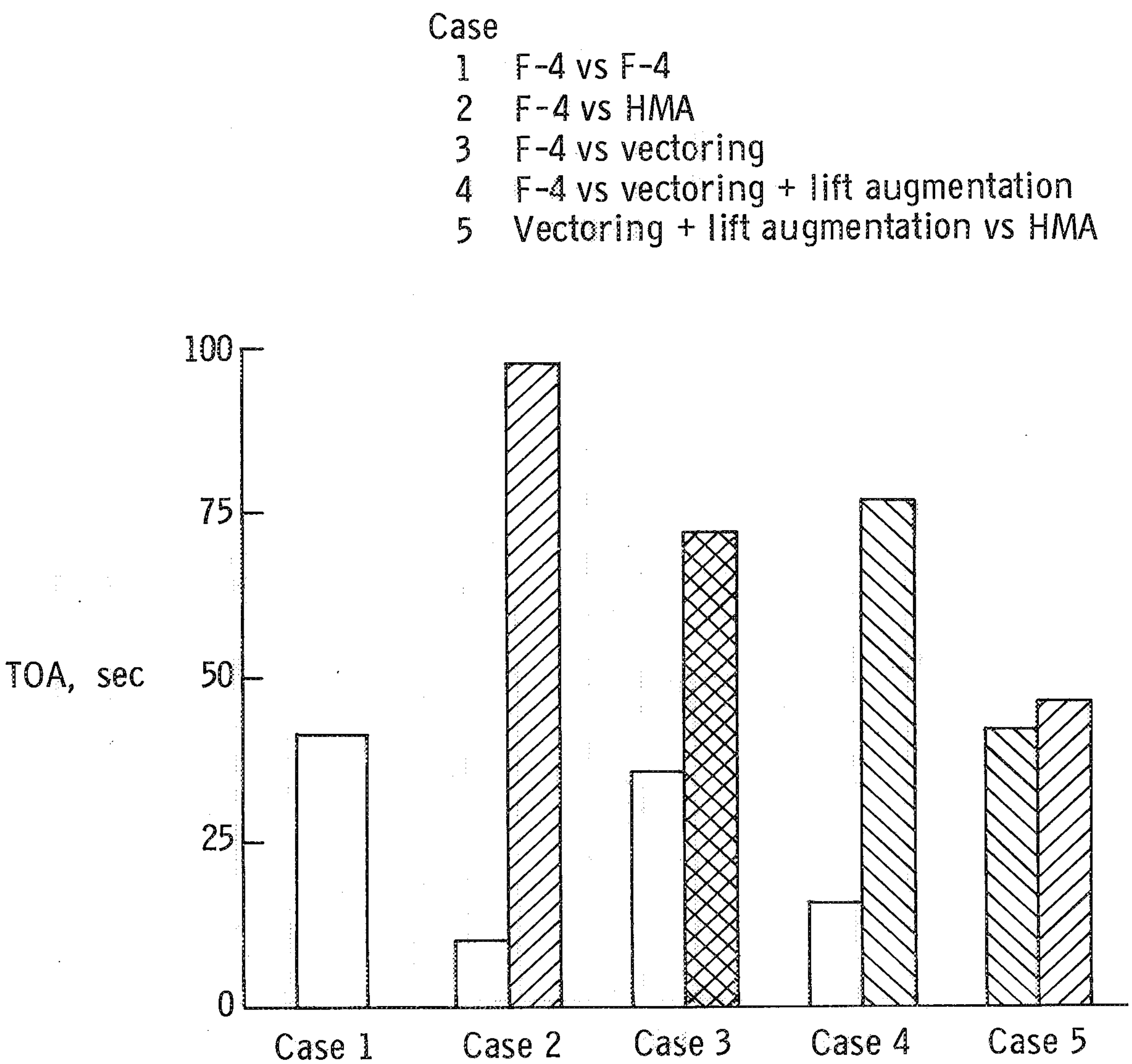

(a) Pilot group 1.




(b) Pilot group 2.

Figure 17.- Percent of TOA in intervals of Mach number and thrust vector angle. Case 5.

[redacted]

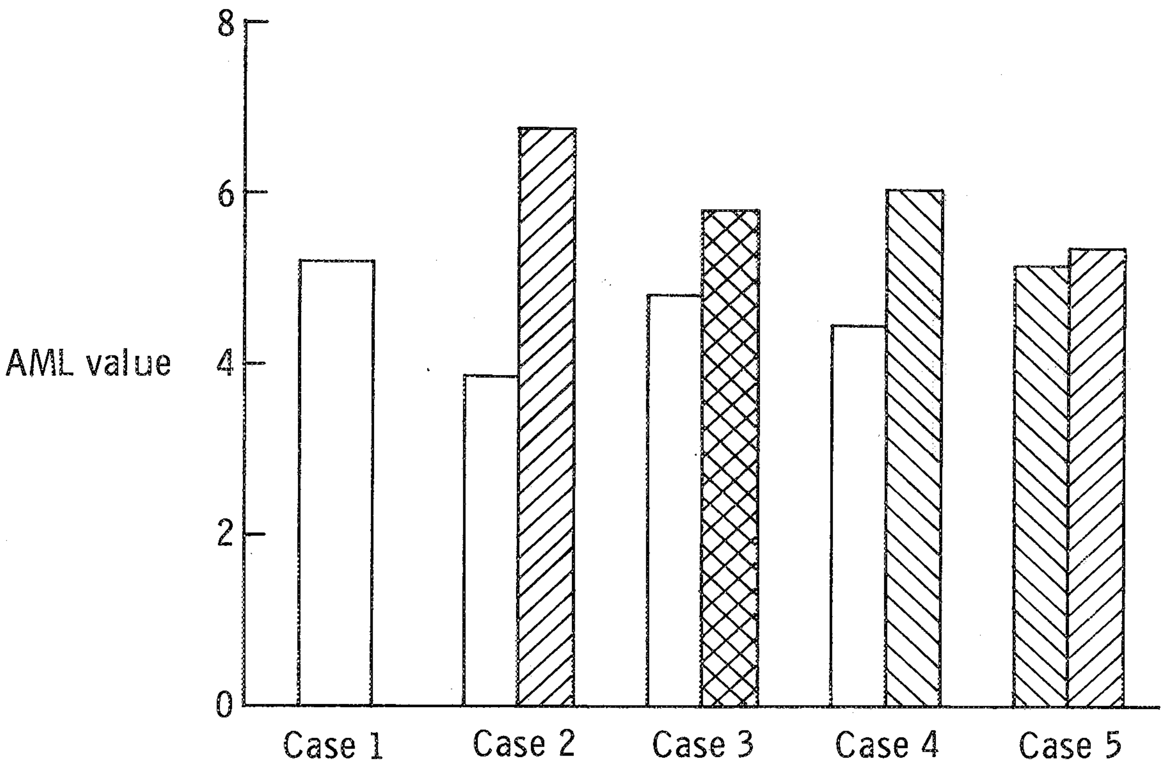



(a) TOA at 180 seconds.

Figure 18.- Results of cases studied averaged over both pilot groups.

[redacted]

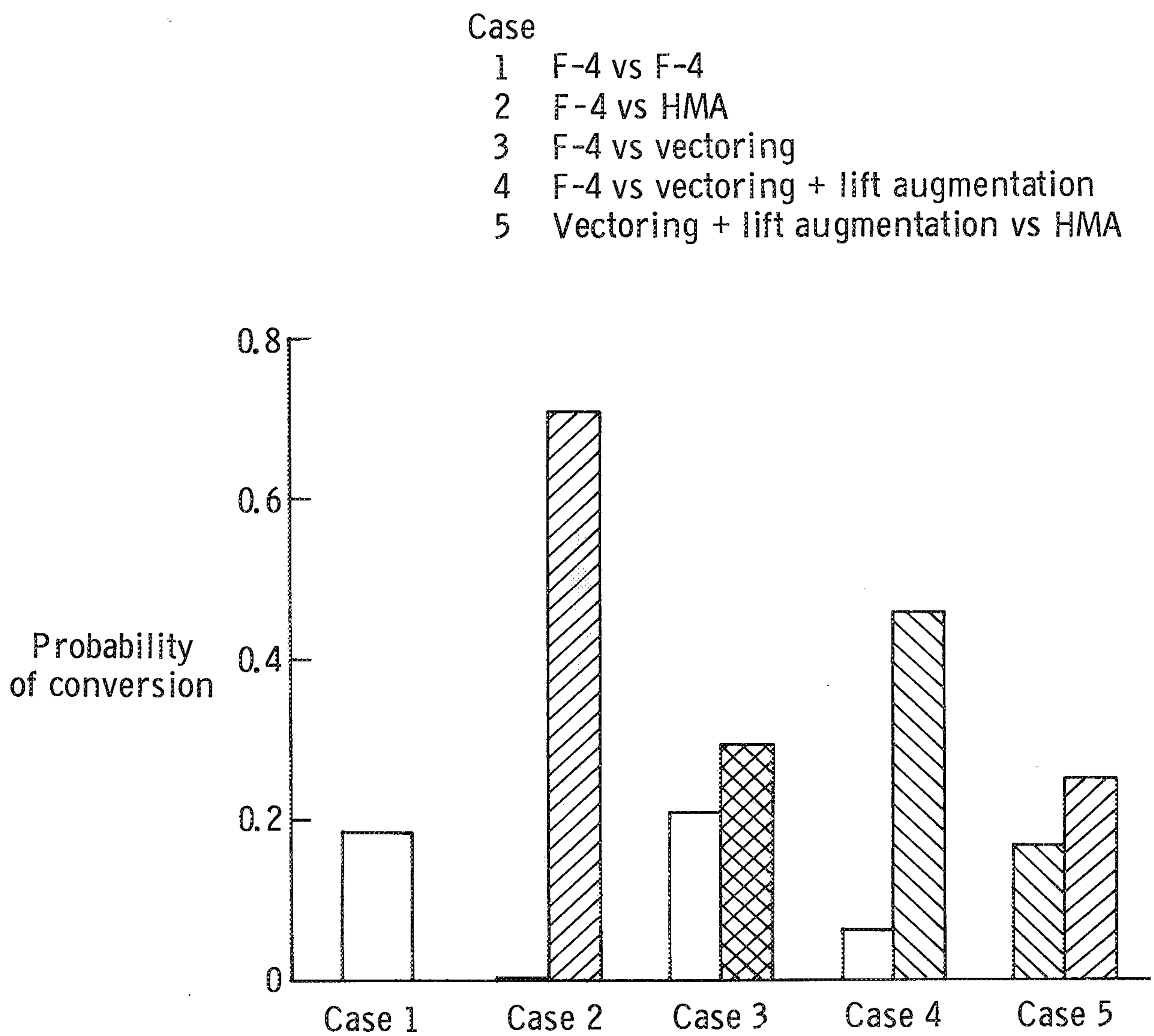
Case
1 F-4 vs F-4
2 F-4 vs HMA
3 F-4 vs vectoring
4 F-4 vs vectoring + lift augmentation
5 Vectoring + lift augmentation vs HMA




(b) AML value.

Figure 18. - Continued.

[redacted]




(c) Probability of conversion.

Figure 18.- Concluded.

[redacted]

[redacted]

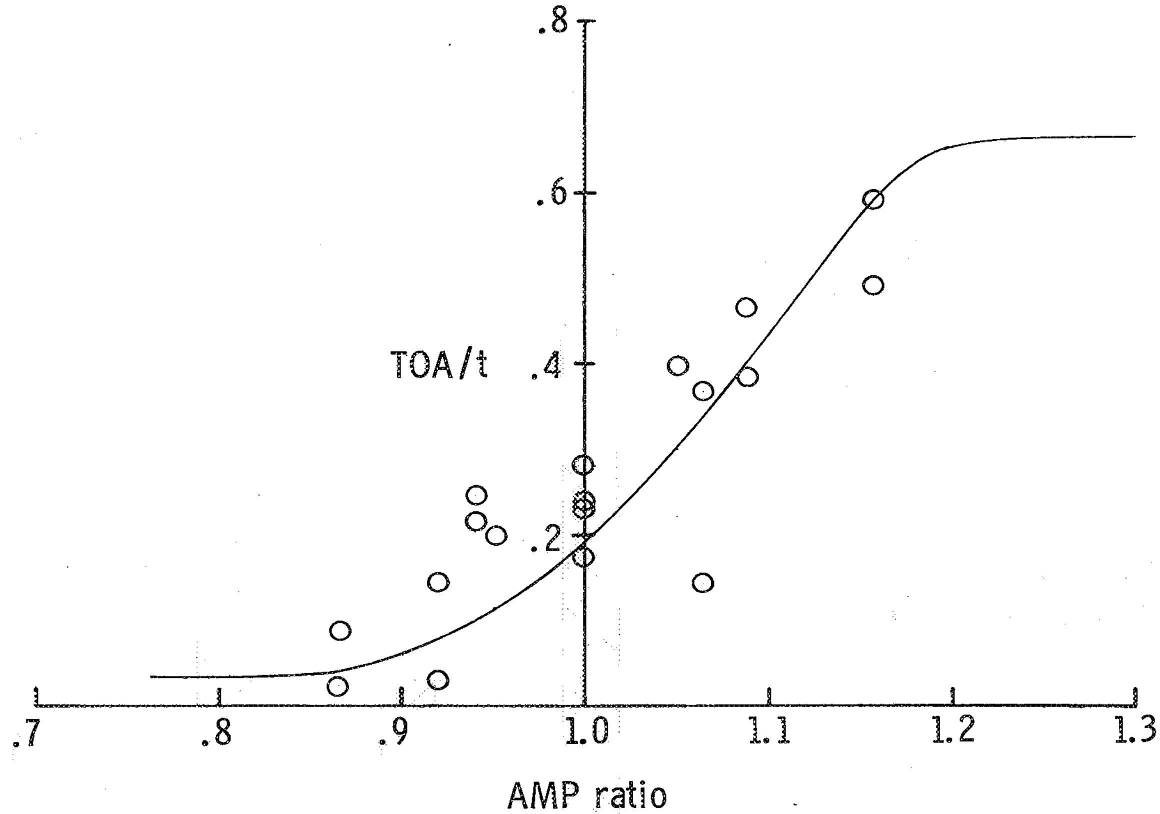



Figure 19.- Aircraft maneuvering parameter.



[redacted]

NASA-Langley, 1975 L-9829

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16. Abstract


As part of a research program to determine the usefulness of advanced concepts for improving the maneuverability of fighter-type aircraft, a simulation study has been conducted to examine the effects of thrust vectoring and induced lift on combat effectiveness. A simulated F-4 aircraft, assumed to have limited (30° maximum) thrust vectoring capability with or without an induced lift component, was flown against two opponent aircraft. One opponent was the same aircraft without vectoring, and the other was a hypothetical aircraft without vectoring but with superior turning performance.



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— National Aeronautics and Space Act of 1958

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